Late Season Tropical Cyclone Formation over the Northeastern Atlantic Ocean: 1975-2005

A Senior Honors Thesis

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by

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ABSTRACT

In the past thirty years, twenty named tropical cyclones formed in the northeastern Atlantic Ocean during the months of October, November, and December. By the accepted definition of a favorable environment for tropical cyclogenesis, most of them should not have developed. The past seven seasons produced ten of the twenty, with 2001 and 2005 spawning three and four systems, respectively.

The study period begins in 1975, the year in which the Hebert-Poteat technique for satellite identification of subtropical systems was published. The northeastern Atlantic is defined as the portion of the Atlantic north of 20°N and east of 60°W. Purely subtropical storms are excluded from the study to focus on the conditions for tropical transformation.

The climatology of the twenty late-season tropical cyclones (LSTCs) is discussed including the peak development periods, location, maximum strength, and type of non-tropical origin. LSTCs in this region arise from four unique origins, providing a method for classification. Type I storms originate as pre-existing, non-frontal and non-tropical cyclones. Type II systems develop along dissipating frontal systems. Type III LSTCs develop directly from an occluded frontal cyclone, while Type IV developments begin with tropical origins. Thirteen of the twenty systems are Types I and II, and the remaining systems are split relatively evenly between Types III and IV.

The environment of each LSTC is examined over the 24 hours prior to attainment of tropical storm status. Wind fields and temperature profiles are calculated on a 13x13 point Lagrangian grid. Wind shear is calculated for the 850-200 hPa, 850-300 hPa, and 850-500 hPa layers. The shear values are averaged on 3x3 point and 1x1 point grids for quantitative comparison of systems. Each system's synoptic environment is visualized on a 41x21 point Eulerian grid centered on (30°N, 50°W) over the 36 hours before genesis; of particular interest are the locations of upper-level troughs, ridges, and upper-level cold lows. With these data the conditions conducive to the formation of LSTCs are analyzed.

I. INTRODUCTION

Late-season tropical cyclones in the Atlantic Ocean have increased in frequency in the past decade. Much of the spike in activity has been located in the northeastern Atlantic basin, outside the more usual development areas. However, the mechanisms of development and the behavior of tropical cyclones in this region are not typical. Between 1975 and 2005, 80% of the late-season tropical cyclones (LSTCs) forming in the northeastern Atlantic north of the Main Development Region (MDR) originated from baroclinic sources: extratropical lows (upper level and surface), decaying fronts, and occluded cyclones. Many transformed into tropical cyclones from established extratropical or subtropical cyclones. However, not all the transformations were completed, and some systems retained a few characteristics of extratropical cyclones, making them true hybrid systems.

Synoptic-scale cyclones (> 100 km) are usually separated into three different categories: tropical, extratropical, and subtropical. Tropical cyclones normally form over the warm oceans of the lower latitudes in the north Atlantic, north Pacific, southwest Pacific, and Indian Ocean basins. Characteristics of tropical cyclones include the presence of a warm core at the upper levels of the system, a non-frontal structure, and deepest convection and maximum wind speeds close to the center of circulation. A warm core means that the air temperature at the center is warmer than the surrounding environment; although difficult to accurately identify without in-situ data, this requirement most clearly defines a tropical cyclone. Tropical cyclones also tend to be smaller than extratropical cyclones, usually spanning fewer than 500 km. Extratropical cyclones have the opposite characteristics as tropical cyclones: a cold core, possible frontal structure, and deepest convection and maximum winds well removed from the center of circulation. Extratropical systems can form over land or water in the middle latitudes (roughly

20º to 60º latitude in both hemispheres), and range in size from less than 500 km to more than 2500 km. Subtropical cyclones exhibit a mix of tropical and extratropical cyclone characteristics, and are best described as a continuum bounded by purely extratropical cyclones on one end and purely tropical cyclones on the opposite end. Horizontal temperature gradients from the upper-level core of the system to the environment tend to be small, but convection and maximum winds are usually still located away from the center. Whether a frontal structure is apparent depends on which end of the continuum the subtropical cyclone is nearest; subtropical cyclones nearing tropical status do not exhibit a frontal structure, and subtropical cyclones closer to extratropical cyclones often have an apparent frontal structure. It is possible for each cyclone class to transition to the other classes given favorable environmental conditions. The transformation of extratropical and subtropical cyclones into tropical cyclones is of particular relevance to this study.

Relatively little research has been done on tropical cyclogenesis from baroclinic sources; only in the last 20 years has interest been kindled in the subject (c.f. Bosart and Bartlo 1991, Davis and Bosart 2003). There are known problems associated with accurately forecasting these hybrid systems. During the 2005 Atlantic hurricane season the National Hurricane Center (NHC), a division of the National Oceanic and Atmospheric Administration (NOAA) which handles the forecasting of tropical weather, struggled with intensity predictions for formerly baroclinic systems. Richard Pasch, a forecaster at NHC, wrote the following passage in a contemporary discussion of then-Tropical Storm Zeta:

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ALTHOUGH A WEAKENING TREND SEEMED IMMINENT EARLIER TODAY...AS THE
LOW-CLOUD CENTER STARTED TO BECOME EXPOSED...A NEW BURST OF DEEP
CONVECTION SUBSEQUENTLY REFORMED NEAR THE CENTER.  ZETA HAS THUS
FAR REFUSED TO WEAKEN IN...WHAT APPEARS TO BE...A STRONGLY SHEARED
ENVIRONMENT.  CLEARLY WE NEED AN INCREASED UNDERSTANDING OF
INTENSITY CHANGE FOR SYSTEMS IN THE SUBTROPICS SUCH AS
ZETA...EPSILON...VINCE...ETC.  NOTWITHSTANDING... GLOBAL MODEL
FORECASTS INDICATE EVEN STRONGER UPPER-LEVEL FLOW OVER THE STORM
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> WITHIN 1-2 DAYS AND IT IS HARD TO CONCEIVE THAT A TROPICAL CYCLONE WILL BE ABLE TO SURVIVE FOR VERY LONG IN SUCH A HOSTILE DYNAMICAL ENVIRONMENT. THEREFORE I HAVE NOT BACKED OFF ON THE FORECAST OF WEAKENING. OF COURSE...ZETA MAY HAVE OTHER IDEAS. (2005)

Tropical Storm Zeta survived another four full days after this discussion was posted, finally dissipating late on 6 January 2006.

There are three aspects to the study of the life cycle of a tropical cyclone: genesis of new systems, intensification of existing systems, and dissipation of existing systems. Some of the most complex changes occur as an area of disturbed weather or, in these cases, an existing baroclinic system transforms into a tropical cyclone. In certain ways, tropical transition is even more complicated because the thermal and dynamic structures of the extratropical cyclone must essentially be reversed: the radius of maximum winds contracts, convection coalesces around the center, and the upper portion of the cyclone becomes warmer than its environment. If the incipient system developed along a front or was occluded, the frontal structure must also dissipate. The order and causal relations of the changes are not entirely known. Because the temporal and spatial criteria of genesis were easy to define and there was limited work published on the topic, this aspect of tropical cyclone research was chosen as the focus for an undergraduate honors thesis.

The next 25 pages will detail the work undertaken and the results found. Section II discusses some literature on purely tropical cyclogenesis, and also two articles which focus on the tropical transition of non-tropical cyclones. Section III describes the methodology, including the data used and calculations completed. Section IV outlines the results: the classification scheme; SST and shear analyses; maximum potential intensity (MPI); and geopotential height field analyses. Section V highlights the conclusions, suggests next steps, and ties both aspects to previous research where applicable. Section VI acknowledges funding sources and important people involved. Section VII contains the reference list, and Section VIII the tables and figures.

II. LITERATURE REVIEW

a. Tropical Cyclogenesis

Hobgood (2005) discussed the development process of a typical tropical cyclone. Tropical waves, which are troughs of lower pressure accompanied by organized convection in the easterly flow over the tropical Atlantic, are the source for most Atlantic tropical cyclones. The convergent surface air flow associated with the tropical wave causes water to evaporate from the ocean into the air, and the air warms. At the center of the disturbance the air is forced to rise, which leads to cooling and saturation. Then the water vapor begins to condense into clouds, releasing latent energy and warming the upper core of the system. Air is now pumped away from the center at the upper levels, and if this divergence exceeds the surface convergence, the surface pressure falls. Surface winds increase, followed by increases in the latent heat fluxes, convergence, and low-level vorticity. In the absence of unfavorable conditions, particularly strong wind shear and excessively dry air, the process becomes self-supporting. Eventually the circulation and convection organize sufficiently to form a tropical cyclone.

McBride (1981) and McBride and Zehr (1981) examined the differences in environment and structure of developing and non-developing tropical systems in the northwest Pacific and northwest Atlantic. This discussion will focus on the Atlantic results since they are relevant to the thesis. The authors identified two problems in studying tropical cyclogenesis: sparse data and diversity of incipient tropical cyclones. Both of these problems impact this study since there is very little in situ data in the northeastern Atlantic, and as will be discussed later, tropical cyclones can arise from four types of incipient system. The articles sorted the Atlantic data into seven categories based on whether the system became a tropical cyclone with winds ≥34 knots: non-developing cloud clusters, non-developing wave trough clusters, non-developing depressions; developing pre-hurricane cloud clusters, developing pre-hurricane depressions, intensifying cyclones, and hurricanes. Rather than look at case studies, the authors made composites of environmental data which were visualized on cylindrical grids of radius 15º centered on the systems. There was a strong diurnal variation in the vertical velocity and mass divergence for developing cloud clusters, with larger values in the morning and smaller at night. For stronger systems, the diurnal variation was much less noticeable. Developing cloud clusters also had small temperature anomalies throughout the vertical, whereas hurricanes had strong positive anomalies at the upper levels and smaller negative anomalies near the surface. The developing cloud clusters also had asymmetric (but roughly bimodal with positive peaks at 800 and 600 hPa) moisture anomalies, whereas hurricanes had a single strong positive peak in moisture around 550 hPa.

For comparison of developing and non-developing systems, McBride (1981) calculated the Seasonal Genesis Parameter (SGP), which was first published by Gray (1977, 1979). This complex parameter is defined as

$$SGP = \left[\begin{pmatrix} Vorticity \\ Parameter \end{pmatrix} \begin{pmatrix} Coriolis \\ Parameter \end{pmatrix} \begin{pmatrix} Vertical \\ Shear \\ Parameter \end{pmatrix} \begin{pmatrix} Ocean \\ Energy \\ Parameter \end{pmatrix} \begin{pmatrix} Moist \\ Stability \\ Parameter \end{pmatrix} \begin{pmatrix} Humidity \\ Parameter \end{pmatrix} \right] \qquad Eq.1$$

McBride (1981) rewrites this parameter as SGP = (Dynamic potential) × (Thermodynamic potential) or

$$SGP = \left[(f)(\zeta_r + 5)\left(1/(S_z + 3)\right) \right] \times \left[(E)(\partial h/\partial p + 5)\left(\overline{RH}\ parameter\right) \right] \qquad Eq.2$$

where f is the Coriolis parameter $2\Omega\sin\varphi$, ζ_r is the 900 hPa relative vorticity, $S_z = |\partial\mathbf{V}/\partial p|$ from 900-200 hPa, E is the ocean heat content integrated from the surface to 60m or 26ºC, h is the moist static energy, and the RH parameter is the piecewise function of mean relative humidity from 500-700 hPa. If RH is <40%, the parameter is 0; if 40%≤RH<70%, the parameter is equal to (RH - 40)/30; if ≥70%, then the parameter is 1.

McBride (1981) found that the SGP for a non-developing depression was half the value of a pre-hurricane depression. For a non-developing cloud cluster the SGP was 1, whereas for a developing cloud cluster it was 12. The magnitude of the Thermodynamic potential term was nearly indistinguishable for developing and non-developing cases, and the difference in total SGP was almost entirely attributable to the Dynamic potential term. The major factor was the low-level relative vorticity parameter, $\zeta_r + 5$.

McBride and Zehr (1981) compared data sets so that the critical features indicating genesis could be determined. Both developing and non-developing depressions had clear anticyclonic outflow at 200 hPa. The warm core was better defined for developing depressions, while the moisture anomaly was stronger in non-developing depressions. Tangential wind speeds were twice as large for developing depressions as for non-developing depressions, and the difference was noticeable over a large area. There were also differences in shear patterns between non-developing and developing depressions. Developing depressions had anticyclonic zonal shear to the north, and near-zero shear over the center. Non-developing depressions had a similar vertical shear pattern, but much more limited in spatial extent. There was also near-zero meridional shear over the center, which extended in a narrow band to the north and south, for both developing and non-developing systems. To the west the shear was positive, and to the east strongly negative. Again, for the developing depressions, the pattern was much more obvious. The authors suggest the Daily Genesis Potential (DGP), defined as

$$DGP = \zeta_{900hPa} - \zeta_{200hPa} \qquad (Eq.3)$$

to distinguish developing versus non-developing cloud clusters and depressions. For both types of non-developing precursors, DGP was half the magnitude of the developing equivalents. The qualification is made that the parameter is only valid for purely tropical systems because baroclinic developments from mid-latitude cold-core systems occur in different processes. The most critical finding was that developing disturbances have strong meridional gradients of vertical shear of the zonal wind and strong zonal gradients of vertical shear of the meridional wind, and that both gradients must persist concurrently for more than one day.

Nieto Ferreira and Schubert (1999) examined Tropical Upper-Tropospheric Troughs (TUTTs) in developing tropical cyclone environments. A TUTT is an elongated trough that is a semi-stationary feature of the upper-tropospheric flow over the oceans in summer. TUTTs are comprised of stationary and eddy (cell) parts; the transient component was the focus of the study. It is known that TUTTs can influence the development of tropical cyclones by changing the magnitude of the wind shear, which can trigger genesis or changes in intensity, and can also affect the movement by altering the steering currents at low- and mid-levels. However, it is not well-known whether the tropical cyclones have any influence on TUTTs. The authors found that TUTT cells tend to form east of tropical cyclones, and that two development processes usually result, depending on whether the shear is cyclonic or anticyclonic. If the shear is cyclonic or weakly anticyclonic, the trough to the east of the tropical cyclone spreads, and an intense TUTT cell is produced. If the shear is strongly anticyclonic, then the new TUTT cell is elongated and therefore weaker.

b. Baroclinic Cyclogenesis

Bosart and Bartlo (1991) published a case study of Hurricane Diana (1984), which formed just east of Florida along an old front. The initial system was baroclinic, but completed the transition to a fully tropical cyclone. They determined that the development and transition process had three steps. First, a potential vorticity maximum triggered development of a wave cyclone along the front. Then strong surface and latent heat fluxes supported convection in the northeast flow along the front. Finally, positive potential vorticity advection created an environment to organize the convection around the subtropical cyclone. The article also lists the conditions believed to be necessary for tropical cyclogenesis: 1) SSTs in excess of 26.5ºC, 2) a pre-existing cyclonic disturbance, 3) a sufficiently strong vertical temperature gradient to support deep convection, 4) sufficient midlevel moisture, 5) low vertical wind shear, 6) environment capable of supporting an upper-level outflow channel. In this thesis, 1), 2), and 5) are the points of analysis.

Davis and Bosart (2003) is particularly relevant to this thesis. They examined baroclinic cyclogenesis during the latter half of the 2000 and 2001 Atlantic hurricane seasons, looking at differences between systems which became tropical cyclones and systems which remained subtropical. Four of the ten tropical systems studied were analyzed in this thesis: Nadine 2000, and Lorenzo, Noel, and Olga (all 2001). Davis and Bosart consider tropical cyclogenesis improbable for 850-200 hPa shear exceeding 15 m s^{-1}, but evidence is accumulating that tropical depressions may actually require some shear to develop. Analysis was run on Aviation (AVN) model data to examine the pre-tropical cyclone shear environment. The authors found that 900-200 hPa shear averaged over a 5ºx5º Lagrangian (storm-centered) grid was at or above 8 m s^{-1} in all ten cases, and actually exceeded the 15 m s^{-1} limit in three of the cases. However, at some point prior to the time of transition the shear had decreased to 6 m s^{-1} or less in all but the case of Noel (2001), which had shear of 10 m s^{-1}. They determined that a combination of baroclinic and diabatic processes created the intense non-tropical cyclones, which then transitioned to tropical cyclones. Intensification by baroclinic forcing most often arose from strong mid-tropospheric temperature gradients, specifically increasing warm advection with height or decreasing cold advection with height. The diabatic causes of cyclone intensification were latent heat fluxes due to phase changes of water from air-sea interaction and the development of convection. For the weaker baroclinic precursors, diabatic heating was much more critical than baroclinic cyclogenesis; the baroclinic structure only served to organize the system and did not intensify it. The cases which transitioned to tropical are those in which the baroclinic system became occluded over SSTs greater than 26ºC.

III. METHODS

The systems composing the subset were selected by spatial and temporal criteria. Late season formation was defined to occur after 1 October; the climatological median of the Atlantic hurricane season is 10 September. To limit the size of the study, the location of formation was limited to the area of the Atlantic Ocean north of 20ºN and east of 60ºW; this area is located directly north of the MDR (Climate Prediction Center 2007). By 1975 two techniques for classifying systems based solely on geostationary satellite imagery were used consistently by NHC. The Dvorak technique is for tropical cyclones (Dvorak 1975), and the Hebert-Poteat technique is for subtropical systems (Hebert and Poteat 1975). Before 1975, identification of a system's tropical or subtropical status was largely subjective. A start date of 1975 was therefore chosen to minimize the impact of classification issues. Purely subtropical systems were excluded from the study in order to focus on tropical cyclone genesis in the region.

Since the intention of this project was to examine the formation environment of LSTCs, genesis had to be defined. Eleven LSTCs had been classified as subtropical and/or extratropical before becoming tropical, so the start of records by NHC was not an appropriate marker. To capture the tropical period, genesis of an LSTC was defined to be the time at which it was classified as tropical by NHC with winds greater than 33 knots. The system's official position was taken from the Atlantic Tracks File 1851-2007, maintained by NHC (Jarvinen et al. 1984). This dataset is a compilation of the best available estimates of systems' tracks and intensities. In some cases the Best Track did not span the required 24 hours from the point of genesis. Earlier points were extrapolated from the existing data, and for more recent systems the NRL satellite archives were also consulted to verify the system's location. The Tropical Cyclone Report on each system was studied to better understand the development process. This document, produced a few weeks after a system's demise, includes an analysis of the life cycle of all systems designated a tropical or subtropical depression or stronger by NHC.

Kalnay et al. (1996) describe the Reanalysis project jointly undertaken by the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). It was intended to quantify the changes produced when the operational Global Data Assimilation System from NCEP's former incarnation, the National Modeling Center (NMC), was altered. The signal (climate change) is separated from the noise (model change). Initially the project was from 1957-1996, with the intent to continue it through the future. It has now been extended back to 1948, and for current data the time lag is only a few days. Some technical aspects of the project will now be discussed. The Global Data Assimilation

System model is ‘frozen’ in time for the entirety of the reanalysis period. Observations are incorporated from ships, pibals, rawinsondes, aircraft, and land surface, among others. Some variables are calculated entirely within the model, and their quality is uncertain (none was used for this project). Extensive quality control was performed on the reanalysis output, and the dataset is considered suitable for weather and short-term climate research.

The NCEP/NCAR Reanalysis 1 data was downloaded using the web interface at the web page of the Physical Sciences Division of NOAA’s Earth System Research Lab (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html). For this project, wind (u and v components) and geopotential data in pressure coordinates were used. The Reanalysis data has a resolution of 2.5º x 2.5º. For wind shear calculations, the closest point to the system’s official center was used as the grid center; if the system was directly between grid points, the motion was then used to determine the direction from which the system had been moving for the previous 12 hours, and that point used.

Reanalysis data are available online in the netCDF format; this format was created by the Unidata division of the University Corporation for Atmospheric Research (UCAR). It can be read on any platform using the provided libraries, and thus allows access with few technical limitations. A 13x13 point (30ºx30º) grid centered on the system was selected for 24, 12, and 0 hours prior to the time of genesis at the 850 hPa, 500 hPa, 300 hPa, and 200 hPa levels. For most models 850 hPa is the standard lower level for calculating shear. The other three levels provided a profile of the upper atmosphere. The netCDF files for the variables u-wind and v-wind were downloaded from the NCEP/NCAR Reanalysis website and interpreted into text format using the Unidata-provided executable ‘ncdump’ run from the command line. The data were then copied into a text file, reformatted, and run through a Fortran program to combine the u and v components and calculate wind shear for the 850-500 hPa, 850-300 hPa, and 850-200 hPa layers. The simple vertical shear equation was used:

$$S = \sqrt{(u_{top} - u_{850hPa})^2 + (v_{top} - v_{850hPa})^2} \qquad (Eq.4)$$

To calculate the wind shear over the center, the average of the nine points around the center of the 13x13 grid was determined. This method captured both the shear directly over the system (the center point) and the local environment (the other eight points). This value was used for comparisons between systems. Contour plots of the larger 13x13 grid were made using IDL to look for areas of low shear relative to the system's center.

NOAA has developed a Sea Surface Temperature (SST) archive which uses optimum interpolation (OI) on in-situ and satellite-derived SST data to create 1ºx1º global weekly SST fields. The method is described in Reynolds et al. (2002); a brief overview will be given here. OI is a statistical technique which makes corrections to a background field (the previous week's analysis, for this case) based on differences between new data points and the background. Weights are assigned to each 'data increment' by the distance between the existing grid point and the new data point, as well as by the variances and covariance errors of both new and old data. It is known that the satellite estimates are biased, and so an estimate of the bias is removed from the data prior to OI. Some ship samples are also biased because of the method of collection, and the satellite estimates have been corrected but not perfected, so the dataset is not problem-free. However, in-situ data for the Atlantic are relatively good because of the U.S. and European buoy networks and the amount of transatlantic shipping. A second version (OI.v2) had some additional changes made, notably a new correction for satellite bias and a change to the sea ice to SST algorithm. The new global mean bias is -0.03ºC. The biggest improvements were poleward of 50º latitude in both hemispheres, where OI.v1 sometimes differed from OI.v2 by 1ºC or more; change in the study region was relatively small (less than 0.25ºC).

Reynolds SST OI.v2 data are available online from the IRI/LDEO Climate Data Library (http://ingrid.ldgo.columbia.edu/). The archives begin in November 1981, which presented a problem because five of the 20 systems formed prior to that time. For now, they are simply left out of the analysis. The available data are archived as weekly averages; when a system formed in the first two days of a period, the previous week's data were collected instead for a more accurate reading. The higher resolution for the SST data necessitated a larger grid for the average; here the 25 points around the center were averaged for a total area of 5ºx5º, the same as for the shear local average. A combination of the Data Viewer tool provided by IRI/LDEO and the Expert Mode option were used to collect the data. Since averages were the only data necessary for this project, the Data Viewer was used to narrow the range for one time per system, and then the switch was made to the Expert Mode. The '[X Y] average' command was added to the resulting code to calculate the average for each time, and any necessary corrections made to the latitude and longitude for the other two times directly in the code. The higher resolution meant that the problem of picking an appropriate grid point was minor for the SST data, but when necessary the same procedure as used with the Reanalysis data was implemented.

DeMaria and Kaplan (1994a) published a relationship between SST and the maximum potential intensity of a tropical cyclone based on data for the Atlantic. The equation is

$$V = A + Be^{C(T-30^{\circ}C)} \qquad (Eq.5)$$

where A = 28.2 m s^{-1}, B = 55.8 m s^{-1}, and C = 0.1813 C^{-1}. T is the SST in ºC and V the maximum potential intensity in m s^{-1}. The 24-hour average SST was used for T.

Geopotential height plots were downloaded from the NCEP/NCAR Reanalysis web page. An Eulerian grid from 100ºW to 0º longitude and 5ºN to 55ºN latitude captured the large-scale environment, in particular the upstream area between the US East Coast, Bermuda, and the Canadian Maritimes. These maps were downloaded for 36, 24, 12, and 0 hours prior to genesis at the 1000 hPa, 500 hPa, 300 hPa, and 200 hPa levels. They were examined qualitatively for movement of troughs, ridges, and upper lows, as well as for the relative strengths of these features.

IV. RESULTS

The details of the 20 systems which fit the study parameters are listed in Table 1. As can be see in Figure 1, half of the LSTCs in the study formed during the 2000-2005 seasons. Development is most common in October and November, with a total of three systems forming in the month of December. Figure 2 is a histogram of genesis dates split into 10-day bins. Few systems form in the middle of the months; there is no apparent physical reason for the paucity. The spike in the 21-30 November bin will be discussed later. The length of the pre-tropical period varied greatly among the LSTCs. Some systems spent days as extratropical or subtropical cyclones, while others appeared to make the transition to a tropical cyclone quickly. Tropical lifetimes also varied greatly over the twenty systems. Some were short-lived as tropical systems, while several maintained tropical status for more than 100 hours. The locations of genesis also varied widely; Figure 3 is an NHC tracking chart with the coordinates at the time of genesis indicated by colored dots. Each color corresponds to a genesis type, which will be discussed next.

A study of the post-advisory analysis in the Tropical Cyclone Reports on each LSTC revealed four types of incipient systems. They are (I) pre-existing, non-tropical and non-frontal disturbance; (II) frontal low; (III) occluded cyclone; (IV) tropical disturbance. There were six type Is, seven type IIs, three type IIIs, and four type IVs in the study set. These categories were then used to divide the results for graphical depiction to search for similar environmental factors. A brief qualitative view of the origins of each LSTC type will now be covered.

Type I systems arose from an upper- or lower-level isolated circulation. Cutoff upper-level cold lows worked down to the surface. Three things then happened, although their order and causation is uncertain at this point: convection increased near the center of the system, the wind speed maximum contracted, and the core warmed. The opposite case is that a surface low worked its way into the upper levels; the same three events must then occur for the tropical transition to be complete. Type I development does not appear to be geographically restricted; both latitude and longitude vary widely among the six Type I LSTCs.

Type II systems form on decaying frontal boundaries that have stalled in the central Atlantic basin. A surface low spins up, usually along the southern end of the front. As the front dissipates, the low separates to become a distinct entity. One possible explanation for the low's formation is that a mid-level vorticity maximum interacts with the front; this explanation is consistent with the findings of Davis and Bosart (2003) and Bosart and Bartlo (1991). One interesting finding was that Type II development is prevalent around (30ºN, 50ºW). Five of the seven Type IIs formed in the vicinity of that location, with three developing during the last week of November and one on 20 December.

Type III systems form when an occluded cyclone loses its frontal structure and gains tropical characteristics. Although existing extratropical lows are the source of this type, it seemed reasonable to separate them into another category because of their distinct thermal structure. The transition process of the thermal structure from the baroclinic extratropical pattern to the relatively uniform tropical pattern is a major question in the field. All three Type III systems developed at high latitudes (greater than 30ºN).

The formation of Type IV systems follows the typical tropical development process reasonably well. For three of the cases, a tropical wave developed a closed circulation as convection increased, which began the vertical pumping of air in the center. The process fed back on itself as the system strengthened. In the fourth case, a surface circulation developed directly below a TUTT, and convection fired near the center. All four systems developed during October of their respective years, and in the southwest part of the study region.

Although the intent of the project was to analyze the formation environment, the relationship between the initial and maximum intensity was also investigated. Figure 4 is a graph of actual maximum intensity versus the intensity at the time of genesis as defined in this study. The same color-coding scheme as in Figure 3 is used here. Note the wide range in initial and maximum intensities present in the subset, and the horizontal asymptote at a maximum intensity of 70 knots. There are actually two systems with initial and final intensities of 65 knots, with the Type I hidden behind the Type III symbol. There is much spread for Types I and II in initial and maximum intensity. Type IIIs transition at relatively high intensity but have average maximum intensities. All the Type IV LSTCs had initial intensities of 35 knots, the minimum wind speed for classification as a tropical storm, and ranged from 35-75 knots for their maximum intensities.

The focal point of the project was analyzing the shear and SST fields for each system in the 24 hours prior to genesis. Figure 5 shows the 24-hour average shear over the 850-500 hPa layer for each system with SST data available versus the 24-hour average SST. Figure 6 is similar, but for the 850-300 hPa layer, and Figure 7 for the 850-200 hPa layer. Three of the Type I systems occurred prior to the start of the SST archive, and one each of Types III and IV; this loss has the most significant impact on the analysis of Types I and III.

The average SST for the 15 systems over the 24 hours prior to genesis is 24.7ºC. Little can be said about the Type I systems with half of the six missing. All the Type II systems occurred after 1981, so discussion of them is more meaningful. Six of the seven Type II LSTCs transformed over SSTs colder than the average of the set, though most of them formed in the southwestern part of the study region. Wind shear magnitudes vary widely for the seven Type IIs, though only one system (Nicole 1998) experienced shear that was consistently higher than the average. Five of the seven had 24-hour average shear values at or below the overall average for each layer. Four of the seven had both lower-than-average wind shear and SST. There were only three type IIIs in the subset, and with the absence of data for Karl (1980) generalizations on shear and SST patterns are impossible for this type. It will be noted that the SST is below average for both systems, which is not unexpected given the high latitude at which the systems developed. Three Type IV LSTCs formed after 1981. The SST for each of the three was significantly higher than the LSTC average, ranging from 26.1ºC to 27.6ºC. This commonality is likely due to their formation in the southwest part of the region, close to the Caribbean Sea, and to the October formation time when the summer heat is still lingering. Wind shear varies widely for all layers, although, like with Types I and III, it is difficult to support generalities.

Figures 8 and 9 are shear contour plots for Lili (1990) (Type I) and Florence (1994) (Type II), respectively, at 12 hours prior to genesis. The grid is 30º square and centered on the system, with the tropical storm symbol indicating the precise location of the LSTC. Note the relative extent of the 5 m s^{-1} contour on the 200 hPa and 300 hPa plots for both systems. In the shallower layer, the contour has expanded over the center of each LSTC. On the plots of Lili, there is also an area of <10 m s^{-1} shear to the north of the system in the shallower layer. In the 850-200 hPa layer, the same area exhibited shear of 15-25 m s^{-1} with a large meridional gradient. The expansion of the 5 m s^{-1} contour is particularly apparent in the Florence plots. Similar patterns exist for most of the Types I and II systems.

Figure 10 has shear contour examples for Types III (Noel 2001) and IV (Tanya 1995). With Noel, there is a small area of light shear directly over the center at 12 hours prior to genesis; this feature also appears in the Karl (1980) and Vince (2005) plots. Tanya is interesting because of the shear gradient over the incipient system. Shear magnitudes are between 10 m s^{-1} and 30 m s^{-1} for this system for the 850-200 hPa layer 12 hours prior to genesis, although an area of lighter shear does exist about 300 nautical miles southwest of the disturbance. The shear is only slightly less for the 850-300 hPa layer. Holly (1976) had a similar pattern of high shear over the center near the time of genesis; Holly and Tanya were the two Type IVs which became hurricanes. Nadine (2000) and Lorenzo (2001) had small areas of low shear directly over the system similar to Types I-III. Nadine and Lorenzo remained tropical storms and had relatively short lifetimes.

Figures 11 and 12 are time-series plots of 850-200 hPa shear during the 24 hour study period. LSTCs which were not previously classified as subtropical or extratropical cyclones by NHC are shown in Figure 11, and transitioning LSTCs in Figure 12. Except for one anomalous Type I transitioning case, the shear values in Figure 12 exhibit less variation at 12 and 24 hours prior to genesis than for the non-transitioning cases in Figure 11. The differences at 12 hours are especially clear; the non-transitioning cases range from 4 m s^{-1} to 15 m s^{-1}, whereas the transitioning cases are 4 m s^{-1} to 9.5 m s^{-1}. Figure 12 suggests that for an established baroclinic system to transform into a tropical cyclone, the shear must fall within a relatively narrow range as the transition occurs.

Maximum potential intensity as calculated from Eq. 5 is plotted in Figure 13 against the system's initial intensity. For this graph only the 15 systems since 1984 are plotted due to the limited SST data. Commentary will be restricted to the Type II and IV LSTCs because of the reduced sample size. Most Type IIs transition at weak to moderate tropical storm strength ($\leq$50 knots) with MPIs near 90 knots. However, Lili (1984) transitioned at 70 knots, nine knots below its calculated MPI. Nicole (1998), which was over relatively warm water, had an MPI-intensity relationship closer to that of the purely tropical systems. The three Type IVs transitioned at 35 knots with MPIs greater than 105 knots, which is more consistent with the typical tropical pattern.

Three hundred twenty geopotential height plots were downloaded from the NCEP/NCAR Reanalysis online archive. The geopotential height fields required study over several weeks to become aware of the commonalities within and between types. Most LSTCs had strong highs at the 1000 hPa level to their north and east. The Type Is frequently had upper-level ridges north of the cutoff lows (the incipient LSTC). Type IIs had little in common with each other at the upper levels. Type IIIs are the least similar of all types at both the surface and upper levels. Type IV LSTCs develop south of strong upper-level ridging. Qualitative similarities and differences will be discussed in more detail for each type in Section V, and a few representative plots are included at the end (Figures 14-17).

V. DISCUSSION

The northeastern Atlantic Ocean produced 20 named tropical cyclones after 1 October between 1975 and 2005. Since 1995 (the start of a relatively active period in Atlantic hurricane activity) 12 LSTCs have developed; in 2005 alone, there were four LSTCs. This area is clearly a small but important source of Atlantic basin tropical cyclone development.

Three of the six factors listed in Bosart and Bartlo (1991) as critical for tropical cyclogenesis were addressed in this thesis. The magnitudes of SST and shear in the 24 hours prior to genesis were calculated, and the types of incipient disturbance began to address the issue of a pre-existing cyclonic disturbance. Since 11 of the 20 LSTCs made the transition from subtropical and/or extratropical, there had clearly been a cyclonic precursor of some duration. One question arising from this material is how cyclonic circulation arises, both in the transitioning systems and in the more tropical cases. A theory in the literature that was addressed in McBride (1981) and McBride and Zehr (1981) is that a vorticity maximum interacts with an area of disturbed weather to induce a cyclonic circulation. This cause would explain Types II and IV, since these systems are not initially cyclonic. For Types I and III, especially the transitioning cases, the original system may have formed more than a week earlier and therefore the relevance of the circulation source is minimal. Eventually, given the predilection in certain circles for analyzing environments in terms of the potential vorticity variable, calculations may have to be done to evaluate its magnitude around the time of genesis.

Figure 4 suggests some relationships between initial and maximum intensity. For all types of LSTCs, the general relationship is that a higher intensity at genesis suggests a maximum intensity not much stronger than the initial. This limitation is probably a result of the baroclinic precursors of most LSTCs. In fact, ten of the 20 LSTCs transitioned at an intensity no more than

10 knots below their ultimate maxima. Nonetheless, there is wide variability in initial and maximum intensity for Types I and II. All three Type III systems transitioned within 10 knots of their maximum intensity. Type IV systems became tropical at minimal storm strength (34 knots), with a 40-knot spread in maximum intensity. Almost no work has been done on the limits of strengthening after transition from baroclinic cyclogenesis; since transition tends to occur at higher latitudes, it is possible that the system does not become purely tropical, and the structure still retains a few baroclinic characteristics. Therefore normal models of tropical intensification may not occur as they do in the deep tropics. Given the number of systems produced by tropical transition, studying this problem through numerical modeling may be a good path to explore.

Davis and Bosart (2003) postulated that tropical transition from a baroclinic system was most likely to occur when a system had occluded over waters with SST > 26ºC. To examine this theory, SSTs were examined for the nine available systems which were listed in the NHC Best Track as having been subtropical or extratropical prior to their tropical classification. Only one of the nine LSTCS, Florence (1994), had an average SST above 26ºC in the 24 hours prior to tropical transition. The average of these LSTCs was 24.2ºC; removing Florence, the average decreased to 23.9ºC. These results do not support the theory of Davis and Bosart in regard to the minimum SST. One possibility is that these transitioning systems do not occlude, but in fact change their thermal structure to a warm core by another mechanism.

Shear in the 850-200 hPa layer was below 15 m s^{-1} for all systems in Figure 7, with an average shear of 8.2 m s^{-1}. These results are consistent with the threshold mentioned in Section II. Only three LSTCs exceeded the average by more than 1 m s^{-1}, suggesting that for most systems the local shear is relatively low. Figures 11 and 12 may also be examined for characteristics described by Davis and Bosart (2003). Davis and Bosart calculated wind shear for the 900-200 hPa layer using a different dataset, so their results are not directly comparable to this study, but the pattern of significant shear reduction should remain similar if their hypothesis is correct. For six of the nine non-transforming cases, the shear minimum in the 24 hours prior to genesis was greater than 6.0 m s^{-1}; the average of the nine cases is 7.3 m s^{-1}. For the LSTCs which transitioned to tropical from baroclinic systems, six of the 11 cases had 24-hour shear minima above 6.0 m s^{-1} with an average of 6.6 m s^{-1}. One of the 11 cases, Peter (2003), had an average shear of 14.9 m s^{-1}, an exceptionally high magnitude. The next-highest was Olga (2001) at 9.1 m s^{-1}. The slightly lower average 850-200 hPa shear for the transitioning cases does provide some support for the assertion in Davis and Bosart (2003) that a reduction in shear is important to tropical transition. The authors did look at time scales further back than 24 hours before genesis, so the significant reductions in shear magnitude seen in their study but not in this research could be attributable to that difference.

Figures 8 and 9 are representative of the most common shear pattern seen over Types I and II developing LSTCs. These LSTCs are embedded in a high shear environment with magnitudes in excess of 20 m s^{-1} within 5º north and south of their locations. However, directly over each system is a relatively small area of shear less than 5 m s^{-1}. McBride and Zehr (1981) found that near-zero zonal and meridional shear was necessary to support a developing system. In this respect Type I and II LSTCs are somewhat similar to the more usual tropical genesis because the LSTCs also have low shear in a highly localized environment around the center. McBride and Zehr (1981) worked with zonal and meridional components of shear separately on the reasoning that in the tropics the zonal component was the more influential. For the latitudes of this research, both components are equally important; however, one future task may be to divide the shear as indicated above and plot the contours to see if the patterns for tropical development are also present for baroclinic sources.

One unique feature of the Type I and II contour plots is that for most of the cases, the extent of the low shear is much larger for the 850-300 hPa layer than for the 850-200 hPa layer. The difference is especially apparent in Figure 9 for the pre-Florence system. A question therefore is raised: is it important? As mentioned in Section I, NHC has considerable difficulty predicting the intensity of LSTCs. Their intensity model calculates shear for the 850-200 hPa layer. Given that the SSTs are often below 25ºC just prior to tropical genesis, it is possible that the vertical structure of LSTCs does not extend as far into the troposphere as their regular-season, southern counterparts. Then the shear calculated by the model would not affect the LSTC, and a shallower layer of shear would be a better estimate of the shear actually affecting the system. The lower magnitude and wider extent of the 850-300 hPa shear minimum supports this hypothesis. For Type IIIs, there is a very small minimum of 850-200 hPa shear close to the center location, but the 850-300 hPa layer is not appreciably weaker in strength or larger in extent. The Type IVs are an interesting set. Holly (1976) and Tanya (1995) became hurricanes within two days of genesis, yet they were directly beneath relatively strong shear with appreciable meridional gradients of vertical shear at the time of attainment of tropical storm strength. Nadine (2000) also developed in a highly sheared environment with strong zonal and meridional gradients across the center; the shear continually increased so that the system's tropical lifetime was limited. Lorenzo (2001) is the odd case of the Type IVs. It developed underneath an area of low shear, similar to the more baroclinic types. Lorenzo also encountered higher shear soon after attainment of tropical storm status, which limited its lifetime.

There are two notable features of Figure 13, the plot of Maximum Potential Intensity as a function of initial intensity. First, the graph for initial intensities lower than 55 knots has the overall shape of a decaying exponential, suggesting that the stronger the system at transformation, the lower the maximum intensity. Above 55 knots there are three systems which do not seem to fit with the left half of the graph, particularly the Types I and III. These systems were located over high SSTs and transitioned at relatively high intensities. For Types II and IV, the best represented of the four types, LSTCs transition at intensities well below the MPI of the environment in which they are located.

The next few paragraphs will discuss some of the features apparent on the geopotential plots. In Figure 14, charts for Lili (1990) at 1000 hPa and 200 hPa are supplied as a roughly representative example. Most of the Type I systems can be seen as cutoff upper-level lows on the 200 hPa charts. Either a ridge is located directly north of the cutoff low or the two are moving towards co-location, except in the case of Ivan (1980), which formed well east of the ridge. In the cases of Ivan, Jose (1981) and Delta (2005), the ridge is elongating ahead of an approaching trough over the US. At the surface, there are strong highs to the north of all systems; for most systems, it is located to the northeast. Only Irma (1978) and Ivan did not have geopotential height increases of 100 geopotential meters (gpm) or more at 200 hPa. All systems had a surface geopotential height increase of at least 25 gpm during one 12 hour period, and the final minimum geopotential height was always higher at the time of genesis than at 36 hours prior to genesis, perhaps suggesting an increase in near-surface heating at the center consistent with tropical transformation.

The Type II systems are the most varied of the four types. Accordingly, charts for Epsilon (2005) and Otto (2004) at 1000 hPa are offered as Figure 15. At 200 hPa, all systems show little change in height (<50 gpm) over the 36 hours immediately prior to genesis. At 1000 hPa, the pattern is more complicated. Nicole (1998), Otto (2004), and Zeta (2005) have constant geopotential height (fewer than 5 gpm of total change). Epsilon (2005) and Florence (1994) show about 30 gpm of net decrease. Olga (2001) has a decrease of 80 gpm, while Lili (1984) has an increase of 75 gpm. The Tropical Cyclone Report for Olga notes that the tropical storm was still embedded in the larger extratropical cyclone, which could explain the unusual drop in geopotential height. Most of the other systems have increasing geopotential heights from 1000-200 hPa; however, two of the Type IVs also show small decreases in geopotential height similar to Epsilon and Florence, which suggests that there may be a closer kinship between Types II and IV than between either of them and Types I and III. The surrounding environment for Type IIs illustrates similar variability. Lili (1984) and Zeta were embedded in zonal upper-level flow, whereas Olga and Otto formed south of weak upper-level ridging, and Epsilon and Nicole formed east of strong ridges. Florence was the unpaired Type II; a strong shortwave trough was sliding north of the upper-level ridge, which was north of the incipient Florence. All but one of the seven Type IIs had strong high pressure to the north and/or east prior to genesis; Epsilon was influenced by high pressure just to its northwest.

Type III LSTCs show the fewest similarities in their geopotential patterns. Figure 16 contains charts for Noel (2001) as examples of the pattern. Karl (1980), despite forming at the same latitude as Noel and Vince (2005) and at nearly the same intensity, is 350 gpm shallower at 200 hPa, perhaps indicating that it was not as tropical as Noel and Vince were. Karl is also sandwiched between ridges in the upper-level flow, although it does have a strong high pressure area to the northeast. Hurricane Vince formed east of the subtropical surface high and the mid-Atlantic upper-level ridge. The pattern on the eastern edge of the plot appeared to indicate that another high was located northeast of the system over Europe, consistent with the other two Type IIIs.

Type IV LSTCs are located southwest of strong surface highs. Plots for Tanya (1995) are added as Figure 17 for visualization of some of the patterns. In the case of Holly (1976) and Nadine (2000), a second high is located west of the incipient LSTC so that the system is squeezed between the highs. There is strong upper level ridging over the LSTC in all four cases, although with Lorenzo (2001) the ridge is extremely elongated southwest to northeast. The plots for Holly and Nadine show troughs exiting the US just prior to LSTC genesis, possibly influencing the tracks and intensities. Holly reached hurricane strength within a day, then rapidly moved to the northeast. Nadine became highly sheared at an intensity of 50 knots and transitioned to an extratropical system. The 200 hPa heights change by 50 gpm or fewer during the 36 hours before genesis.

Two additional parameters the author would like to analyze are DGP and (possibly) SGP. The DGP parameter is relatively easy to compute since it is a vertical difference of relative vorticity, and it may be enlightening to examine the changes every 6 hours for the 36 hours prior to genesis. The most significant changes will likely be in Type II and IV LSTCs because the pre-existing disturbance is not an extratropical cyclone. McBride (1981) noted that the Dynamic potential term of SGP was most indicative of imminent genesis. The Thermodynamic potential term may reveal more for baroclinic systems than for tropical disturbances since the environment must change markedly to produce deep convection near the center of the system. It would also be interesting to compare the Thermodynamic potential term of systems which remained subtropical to the values of those which completed tropical transition.

Examination of LSTC temperature and moisture profiles is another area for future work. For a full transformation into a tropical cyclone, the system must produce deep convection close to the center of circulation. These variables are indicative of the potential for convection, although because the systems are relatively small in size the Reanalysis data is somewhat coarser than necessary to resolve the local features. However, broader changes will be readily picked up in the output.

Tropical cyclones in the northeastern Atlantic basin have four unique origins, three of which are non-classical. The classification scheme based on the type of incipient system appears to work well for development in this region. The types have geographic commonalities in their formation. Most Type IIs were clustered around (30ºN, 50ºW), while the Type IIIs formed poleward of 33ºN. The Type IVs originated in the southwestern section of the study region, closer to the tropics. Some environmental similarities occur within individual types, particularly for Types II and IV with respect to SST. With the exception of the Type IVs, the systems' SSTs were usually lower than the historical formation threshold of 26.5ºC. For all but one LSTC, SSTs were above the climatological mean for the region; for Noel (2001), the SST exceeded the climatological mean by 1.9ºC. These low SSTs appear to indicate that the typical tropical development process is not the usual means of tropical cyclone formation in this area.

Wind shear patterns vary widely between types, and few conclusions can be drawn with just three data points. One of the next steps is to calculated wind shear at the intermediate periods of 6 hours and 18 hours prior to genesis to better understand the timing of fluctuations in shear magnitude in the formation environment. For systems which transitioned from established extratropical or subtropical cyclones, the shear magnitude was usually 4-10 m s^{-1} at 12 hours prior to transition. For non-transitioning cases, the shear at this time was 4-14 m s^{-1}.

Development of Type I, II, and III LSTCs occurred under a shear minimum, suggesting a highly localized favorable environment. Type I and II LSTCs showed clear differences in the horizontal extent of the shear minima. For the 850-300 hPa layer, the low shear area was significantly larger than for the 850-200 hPa layer. One possible effect is that LSTCs over cool water have a lower vertical extent than do systems in the warmer tropics because the diabatic processes do not support deep convection. Then the higher shear at 850-200 hPa may not affect the system. This theory will be explored in future work, first by evaluating the local vertical temperature gradients and adding the 850-400 hPa and 850-250 hPa layers to the shear analysis, and much later by numerical modeling. More work needs to be done on the geopotential height fields to improve on the qualitative description discussed earlier.

VI. ACKNOWLEDGMENTS

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VIII. TABLES AND FIGURES

Table 1. List of 20 tropical cyclones identified as LSTCs. Included data are: the date on which the system was classified as tropical with winds 34 knots or higher; position and intensity; and formation type.

Storm Name	*Year*	*Date*	*Lat*	*Lon*	*Initial Intensity (kts)*	*Type*
Holly	1976	23 Oct	22.5	58.0	35	IV
Irma	1978	4 Oct	35.1	31.5	40	I
Ivan	1980	4 Oct	35.6	24.6	40	I
Karl	1980	25 Nov	37.7	44.7	65	III
Jose	1981	30 Oct	27.7	46.6	35	I
Lili	1984	20 Dec	31.1	52.4	70	II
Lili	1990	11 Oct	31.2	55.9	65	I
Florence	1994	4 Nov	26.0	52.6	35	II
Tanya	1995	27 Oct	26.2	57.9	35	IV
Nicole	1998	24 Nov	27.9	29.1	35	II
Nadine	2000	20 Oct	30.4	57.2	35	IV
Lorenzo	2001	30 Oct	28.5	44.6	35	IV
Noel	2001	5 Nov	37.8	50.3	65	III
Olga	2001	24 Nov	29.5	49.8	50	II
Peter	2003	9 Dec	20.0	37.4	40	I
Otto	2004	30 Nov	31.3	51.0	40	II
Vince	2005	9 Oct	33.8	19.3	55	III
Delta	2005	23 Nov	27.4	41.2	50	I
Epsilon	2005	29 Nov	31.5	49.2	45	II
Zeta	2005	30 Dec	24.2	36.1	40	II

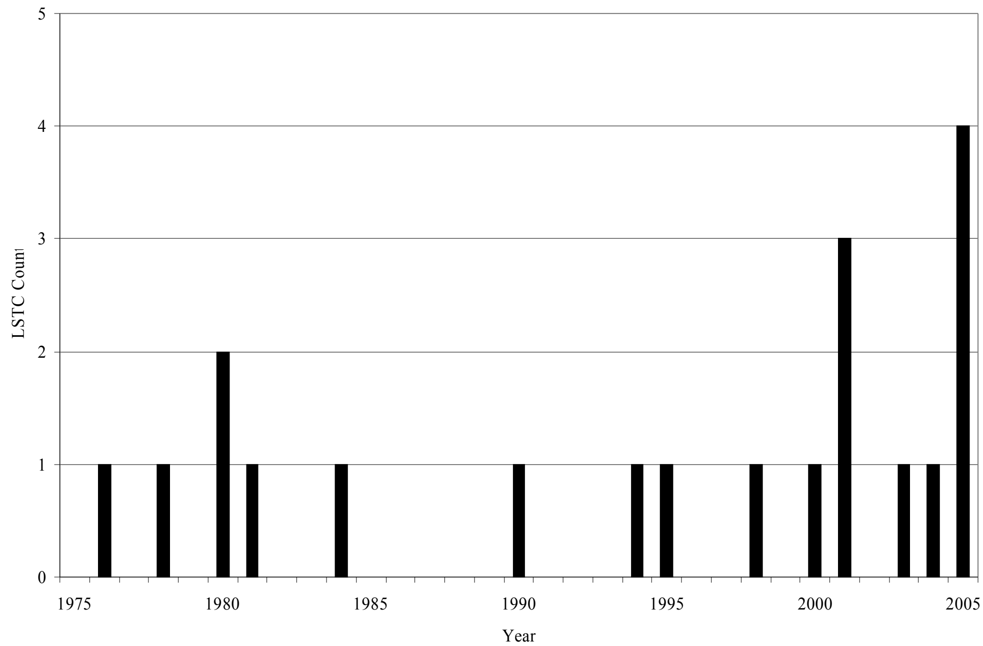


Figure 1. Histogram of LSTCs by year during the study period (1975-2005).

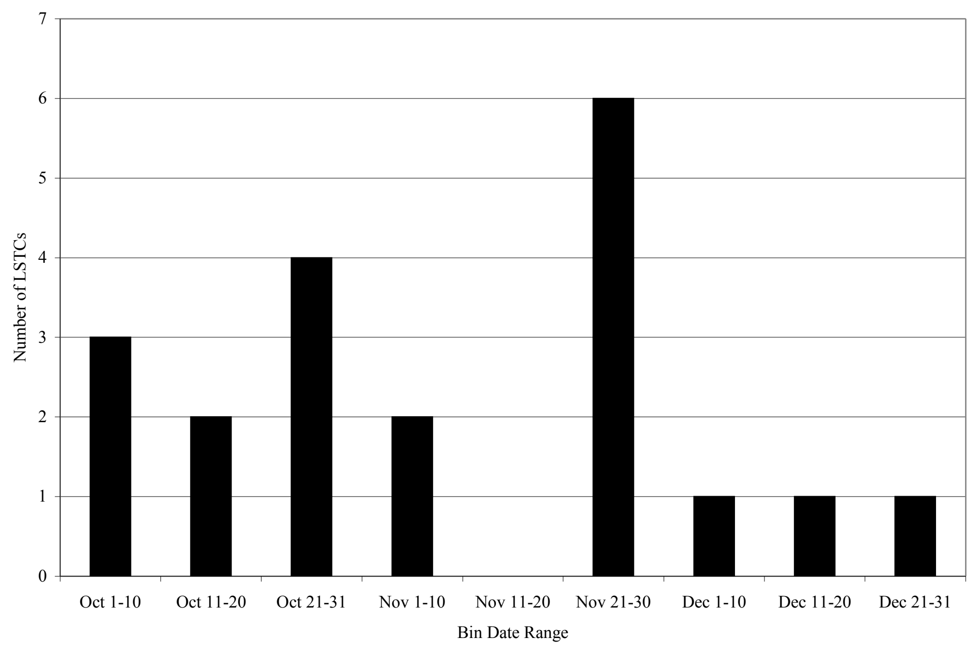


Figure 2. Histogram of LSTC genesis dates binned into seven 10-day and two 11-day periods.

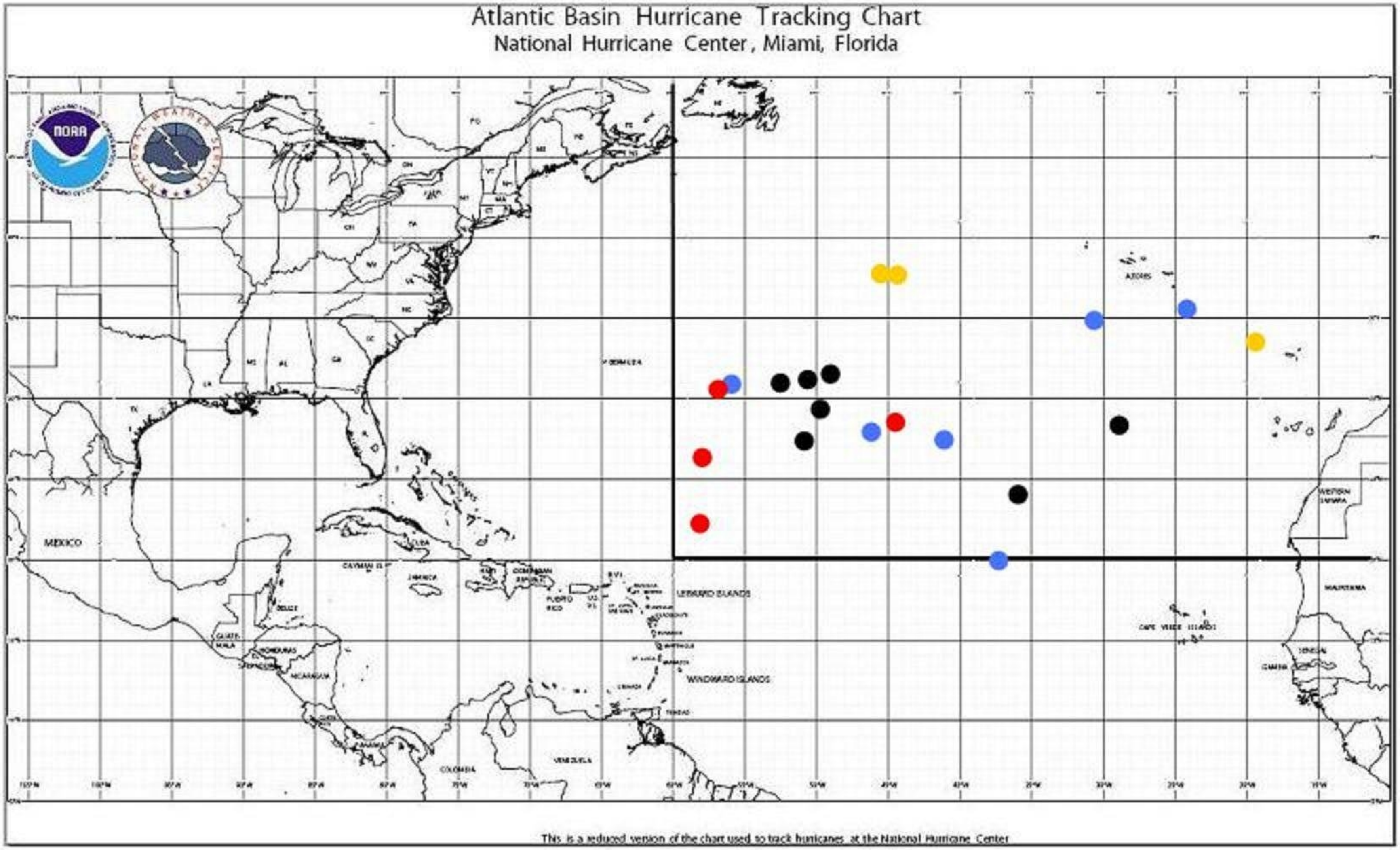


Figure 3. Position of each LSTC at time of genesis. Thick black lines demarcate spatial boundaries for the study.

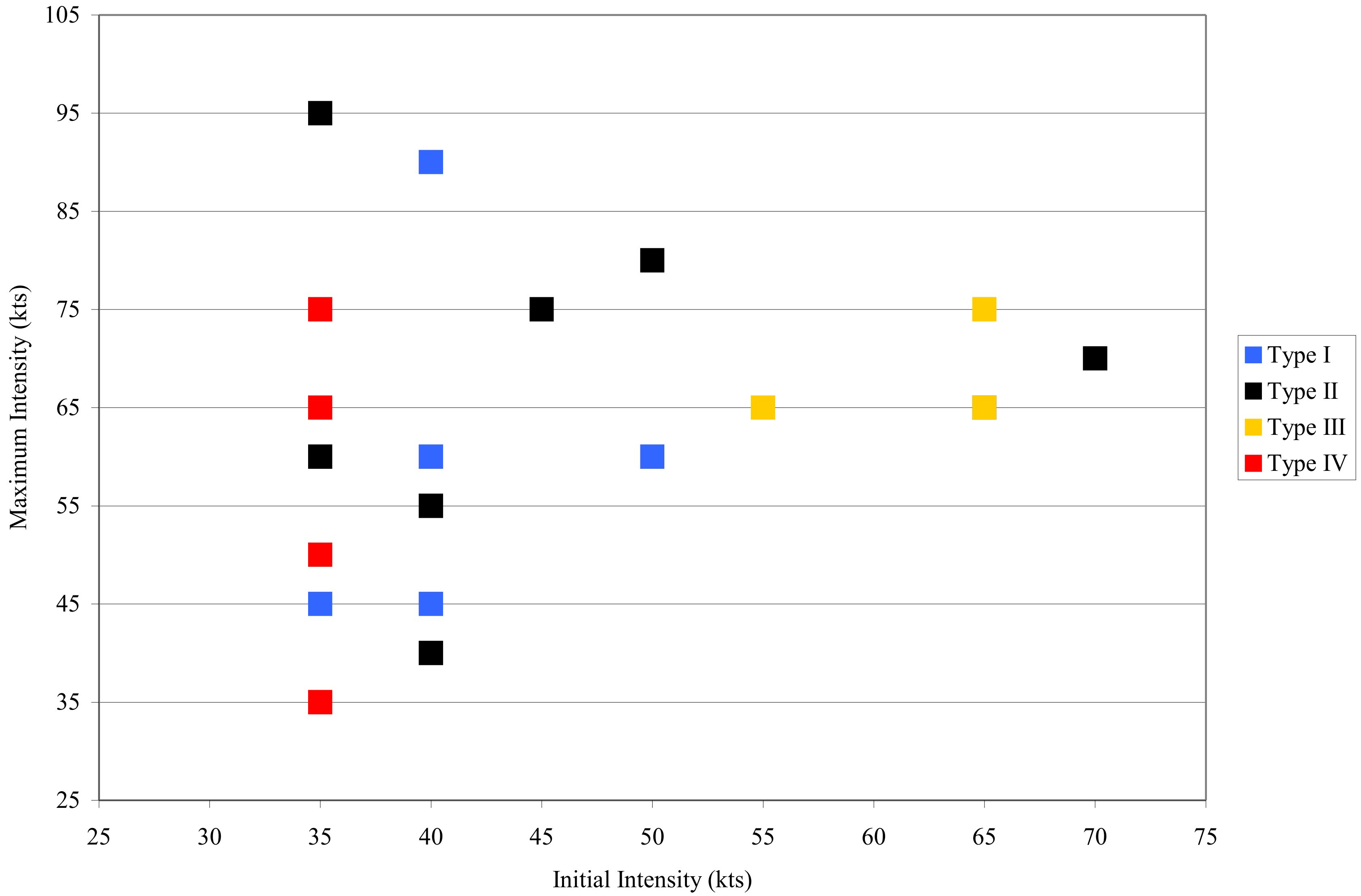


Figure 4. Plot of actual maximum intensity versus the intensity at the time of genesis.

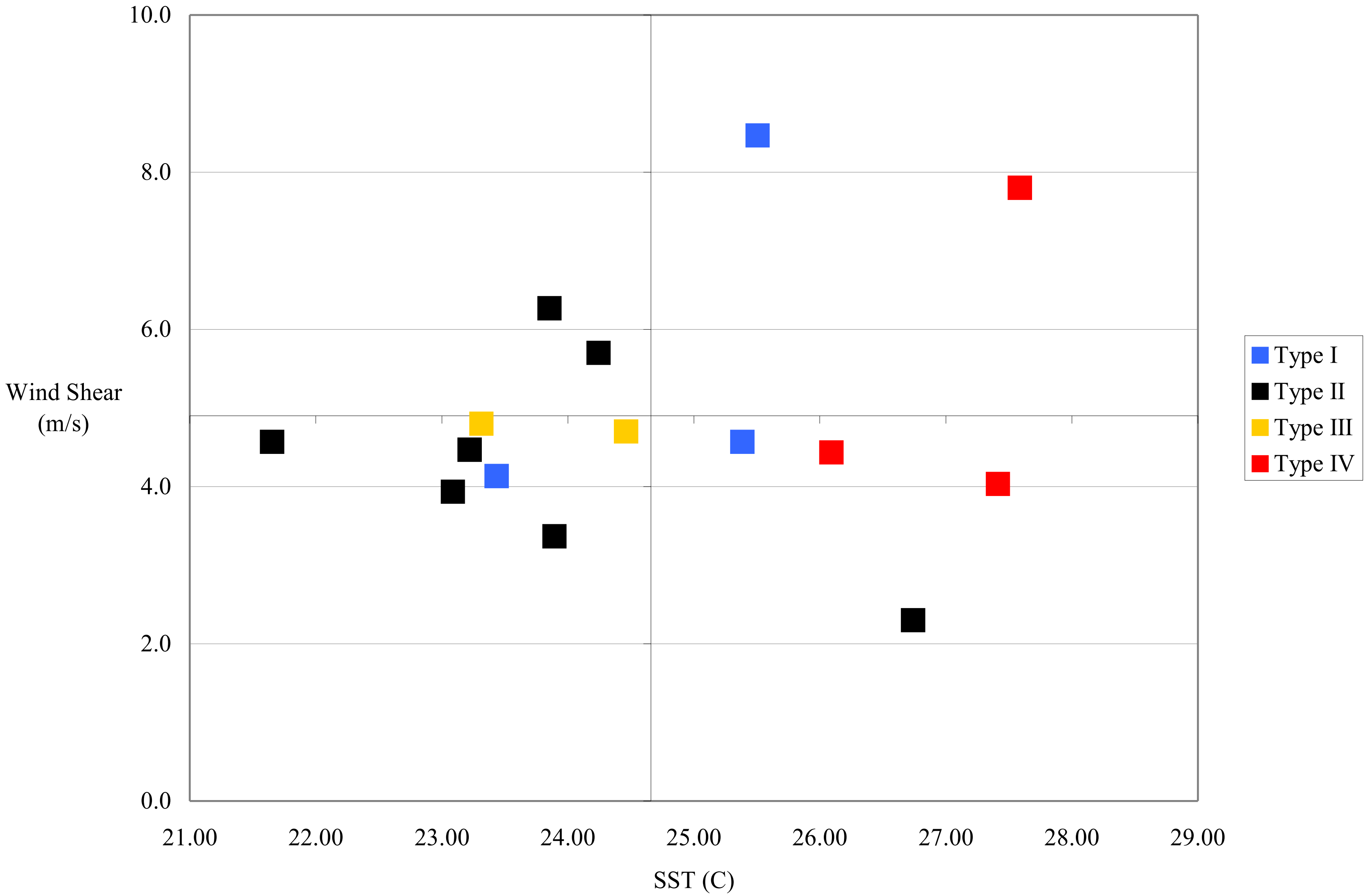


Figure 5. Plot of wind shear for 850-500 hPa layer versus SST. The ordinate and abscissa are set to cross at the averages.

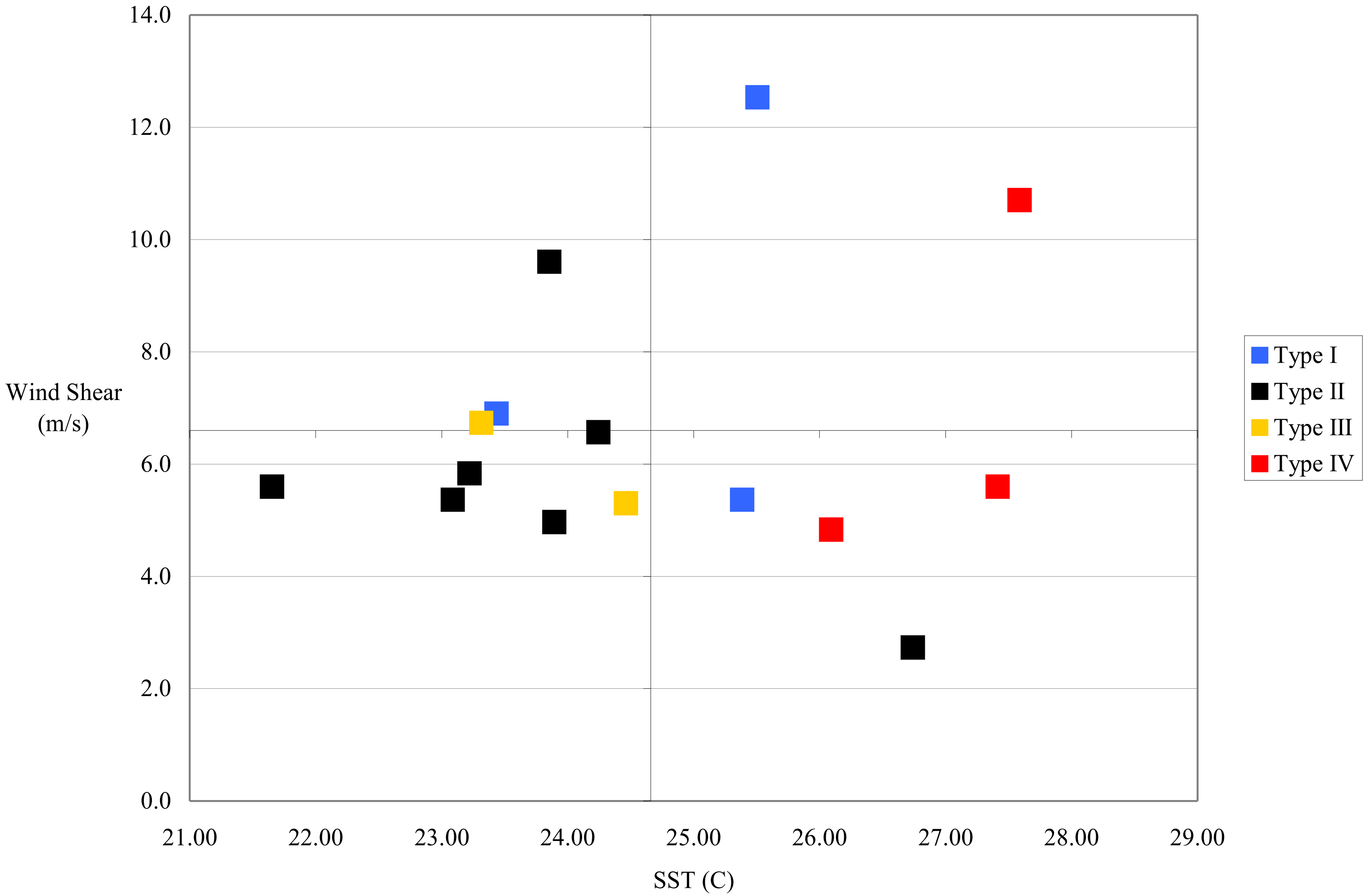


Figure 6. Plot of wind shear for 850-300 hPa layer versus SST. The ordinate and abscissa are set to cross at the averages.

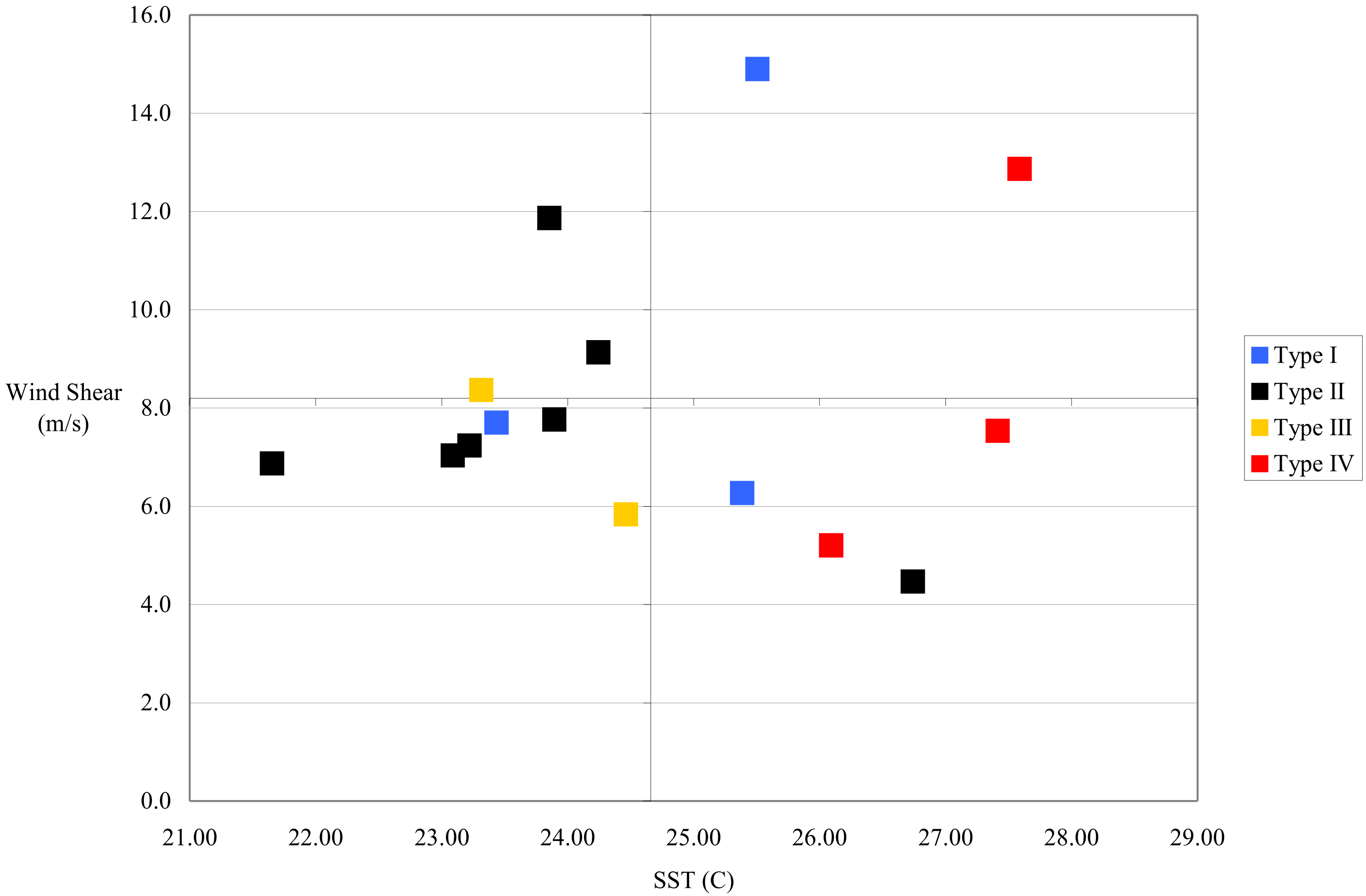


Figure 7. Plot of wind shear for 850-200 hPa layer versus SST. The ordinate and abscissa are set to cross at the averages.

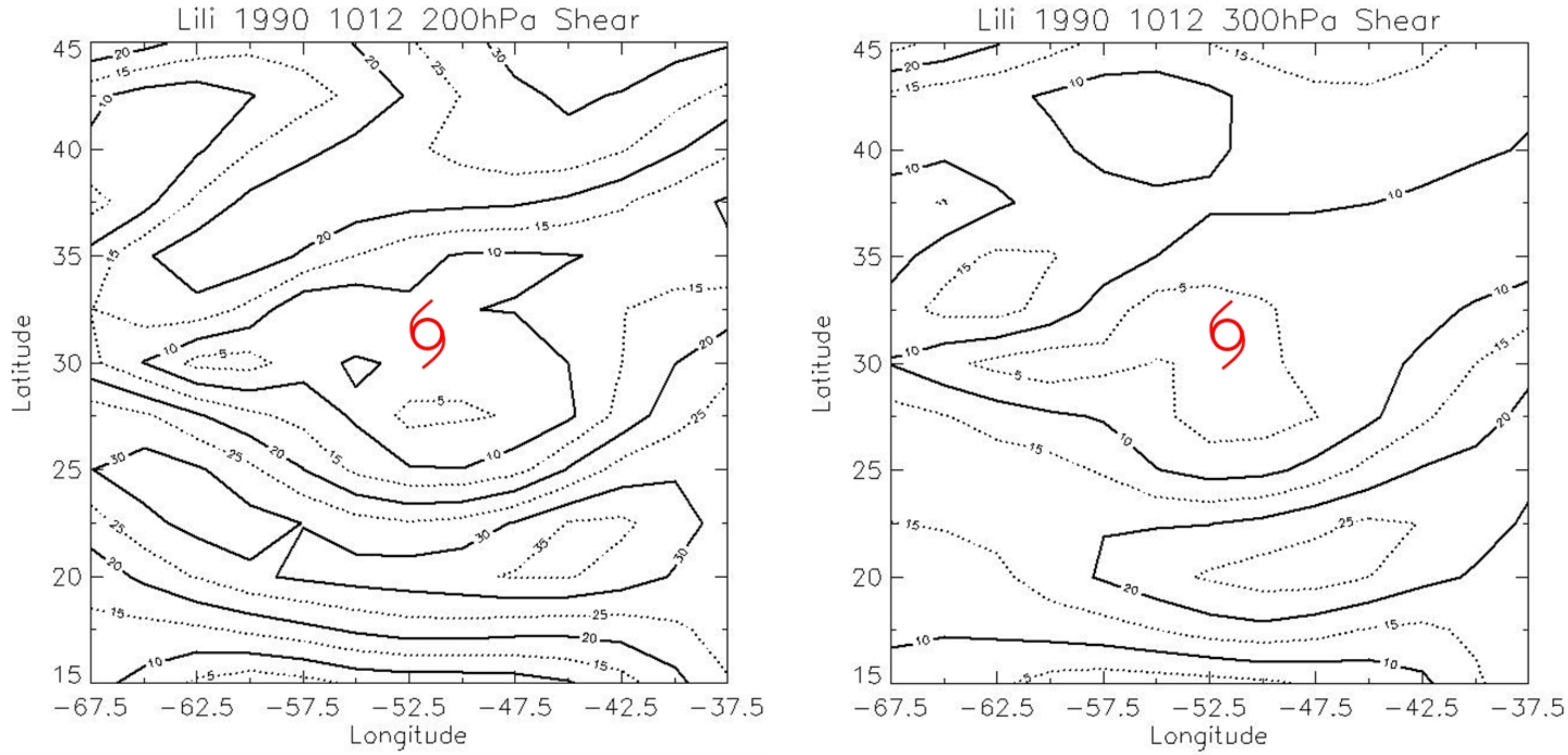
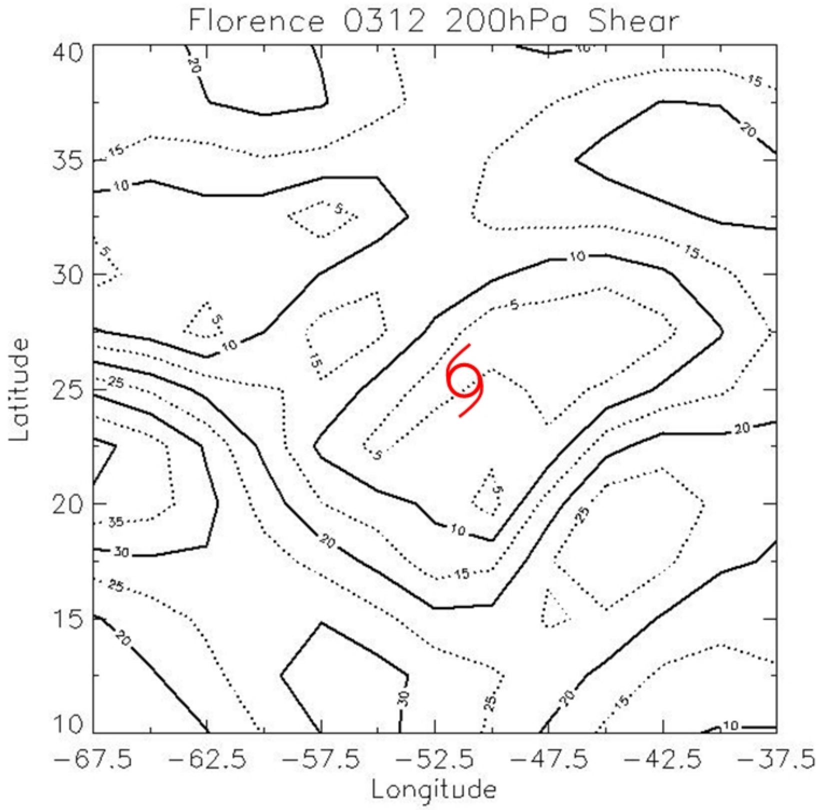


Figure 8. Shear contour plots for Type I Lili (1990) on 10 October at 12Z, 12 hours prior to genesis. Left is 850-200 hPa shear, right is 850-300 hPa shear. Tropical storm symbol indicates the current position of Lili.



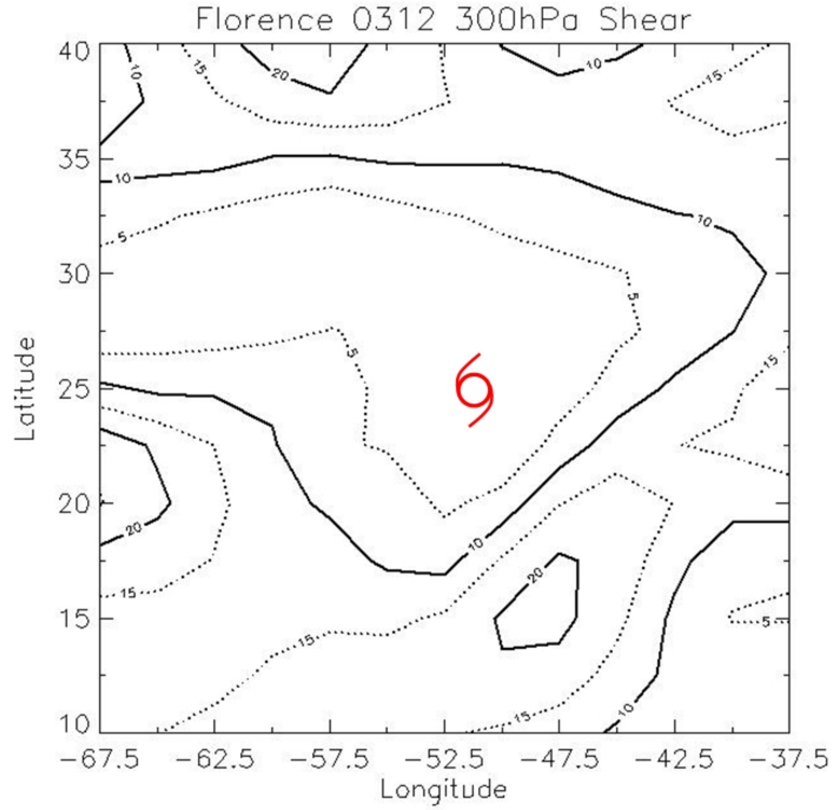


Figure 9. Shear contour plots for Type II Florence (1994) on 3 November at 12Z, 12 hours prior to genesis. Left is 850-200 hPa shear, right is 850-300 hPa shear. Tropical storm symbol indicates the current position of Florence.

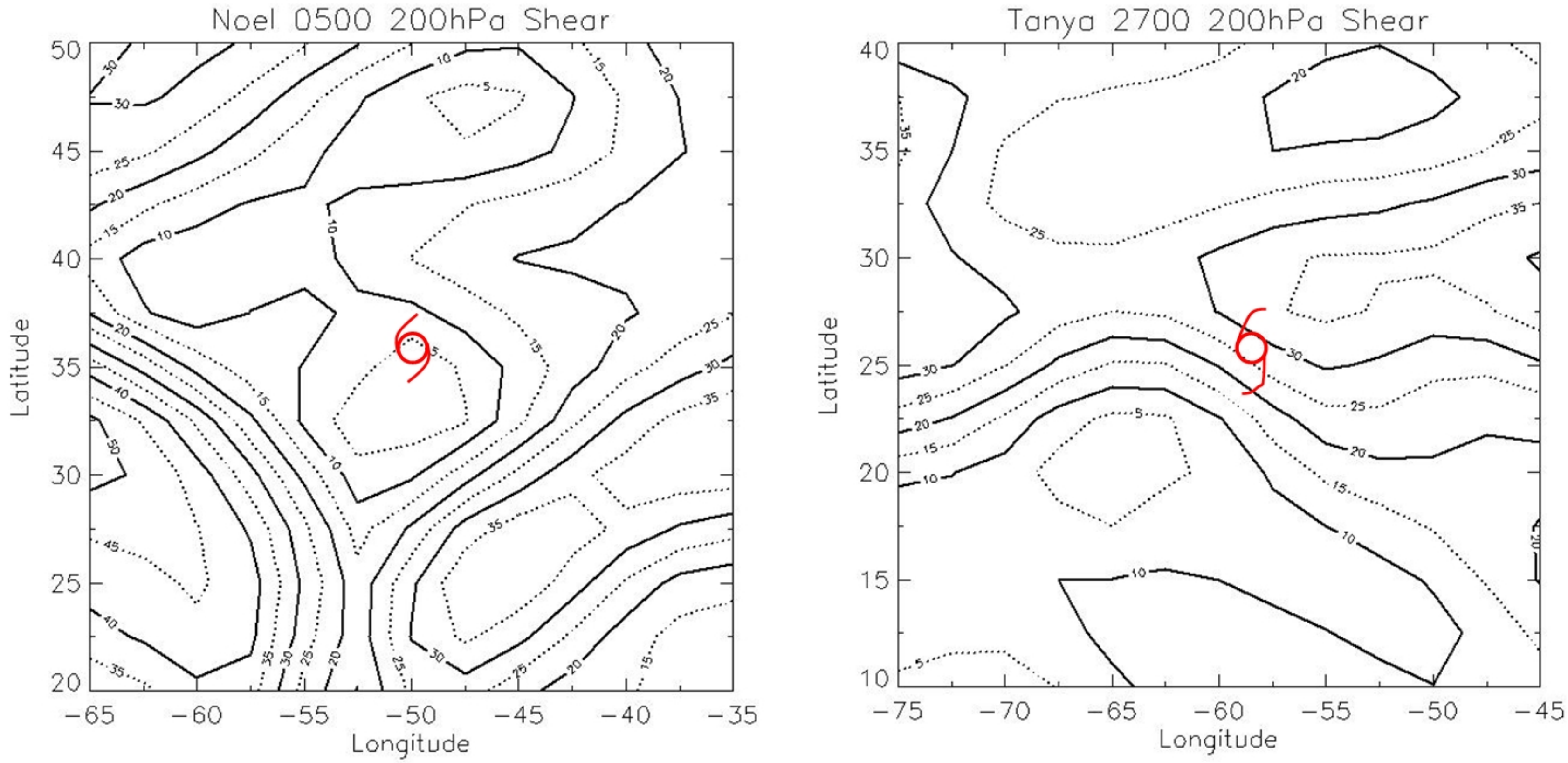


Figure 10. Shear contour plots for (left) Type III Noel (2001) on 5 November at 0Z and (right) Tanya (1995) on 27 October at 0Z, 12 hours prior to genesis. Both are 850-200 hPa shear. Tropical storm symbol indicates the current position of each system.

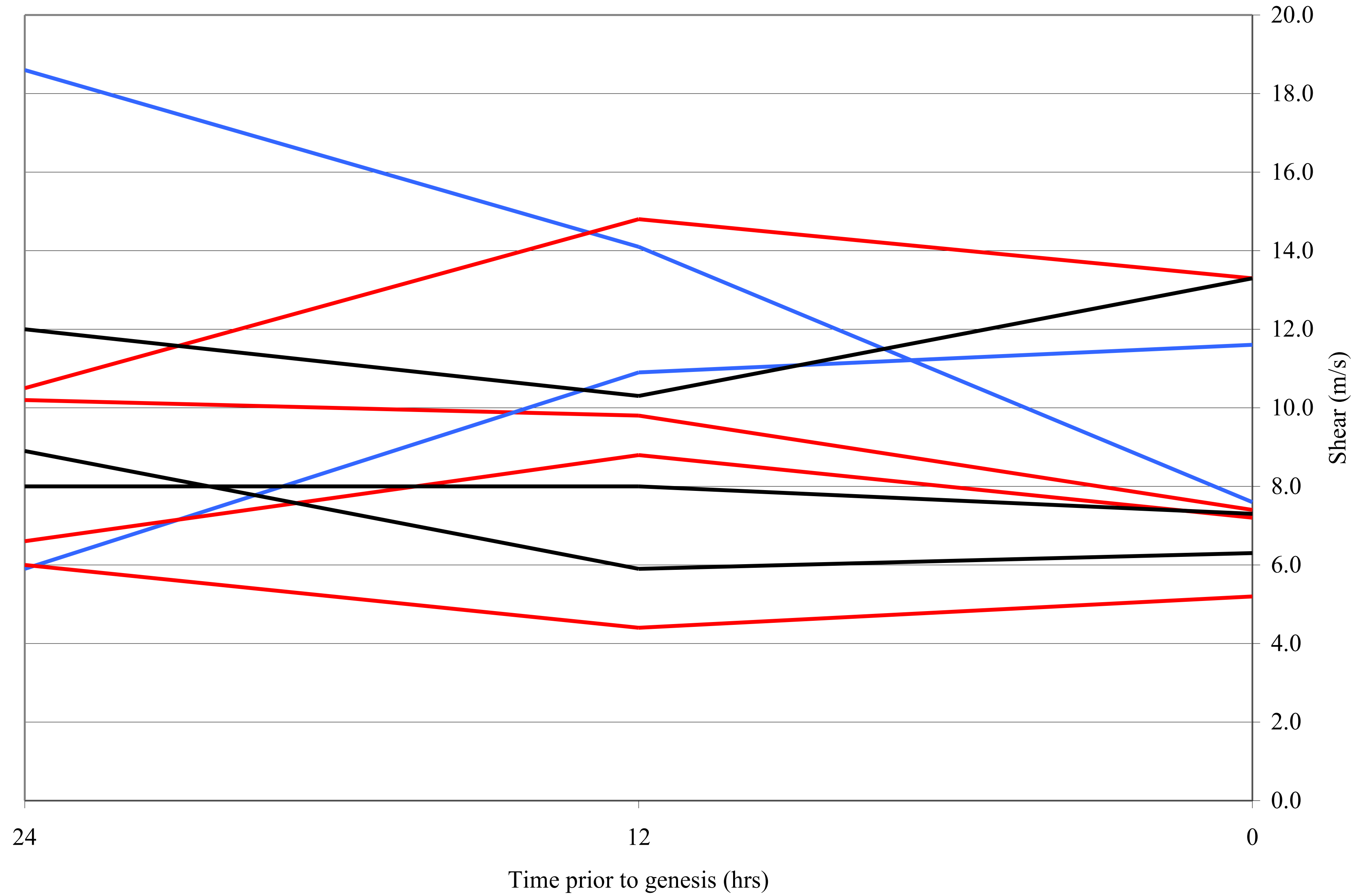


Figure 11. Time series of 850-200 hPa wind shear for non-tropically transitioning LSTCs; Type color scheme retained.

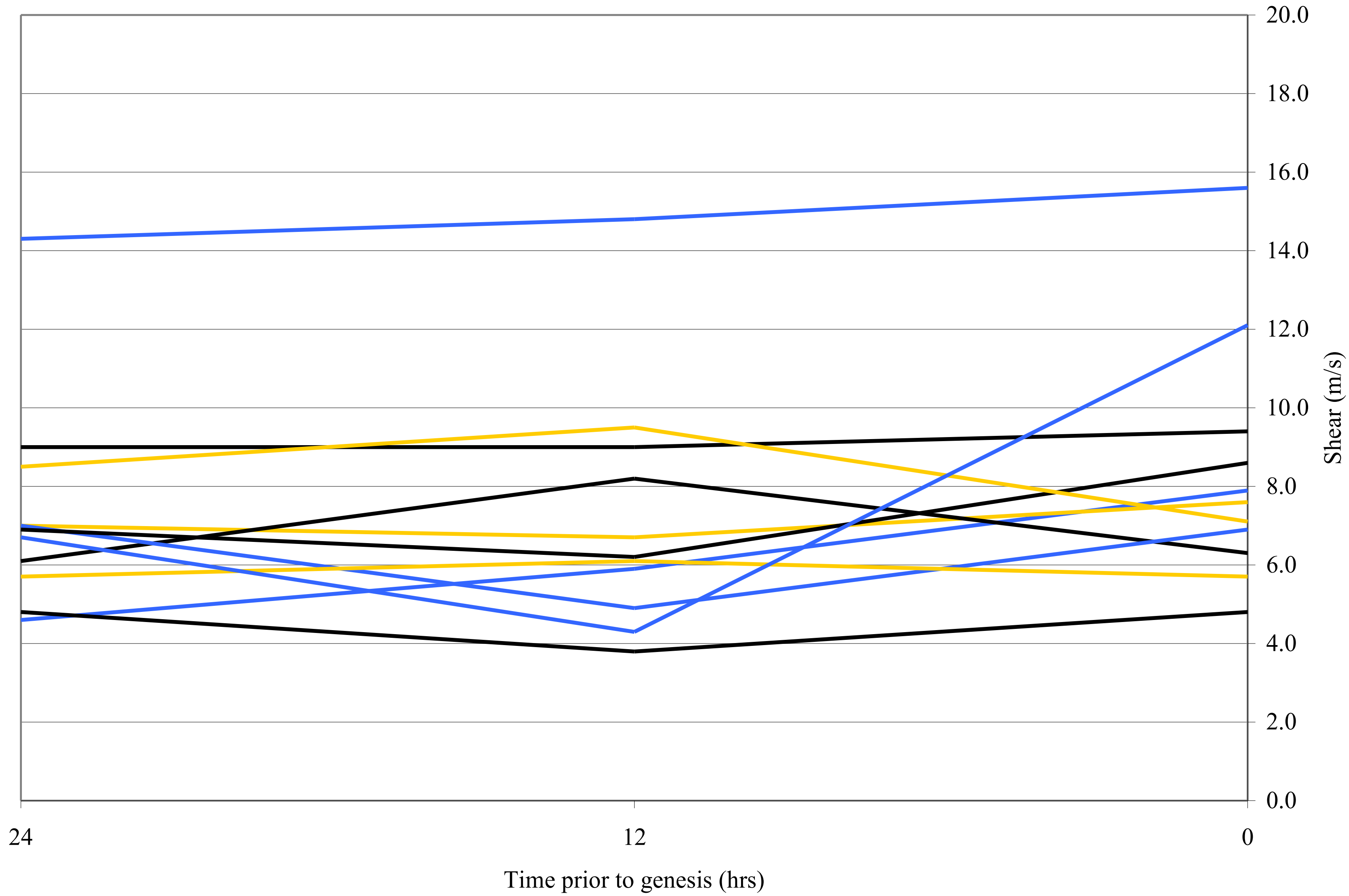


Figure 12. Time series of 850-200 hPa wind shear for tropically transitioning LSTCs; Type color scheme retained.

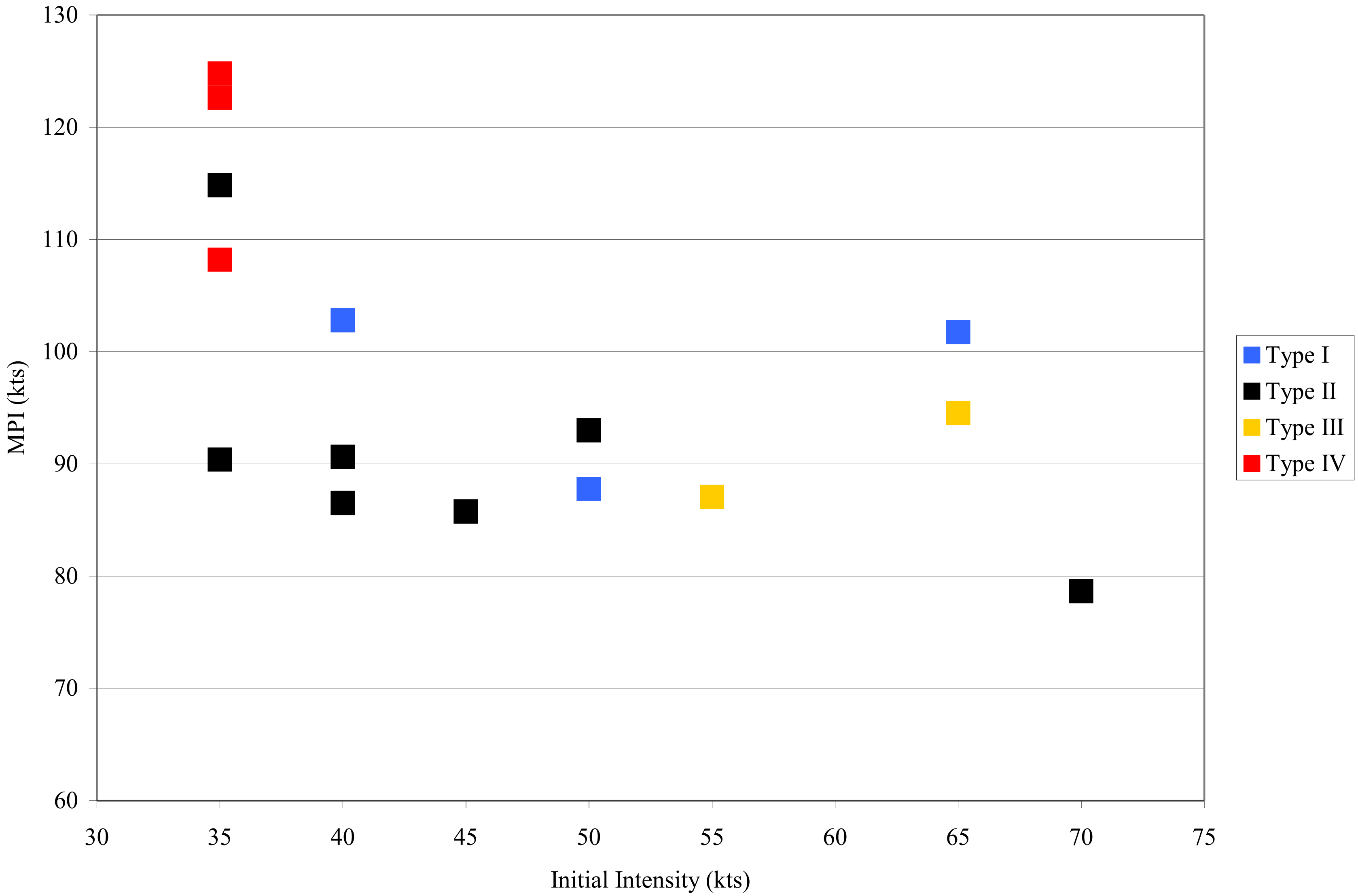
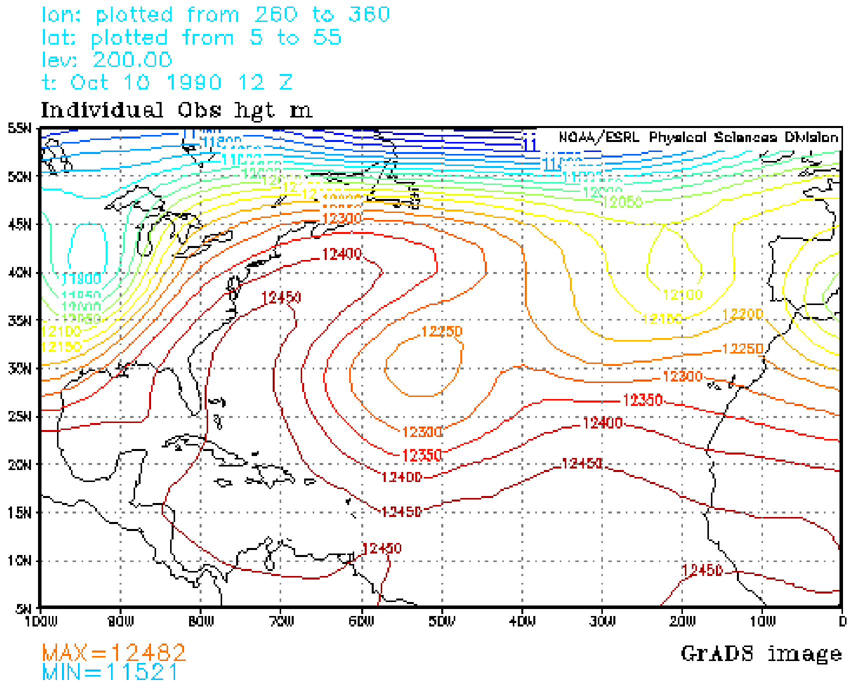


Figure 13. Plot of Maximum Potential Intensity (MPI) in knots versus intensity at genesis.



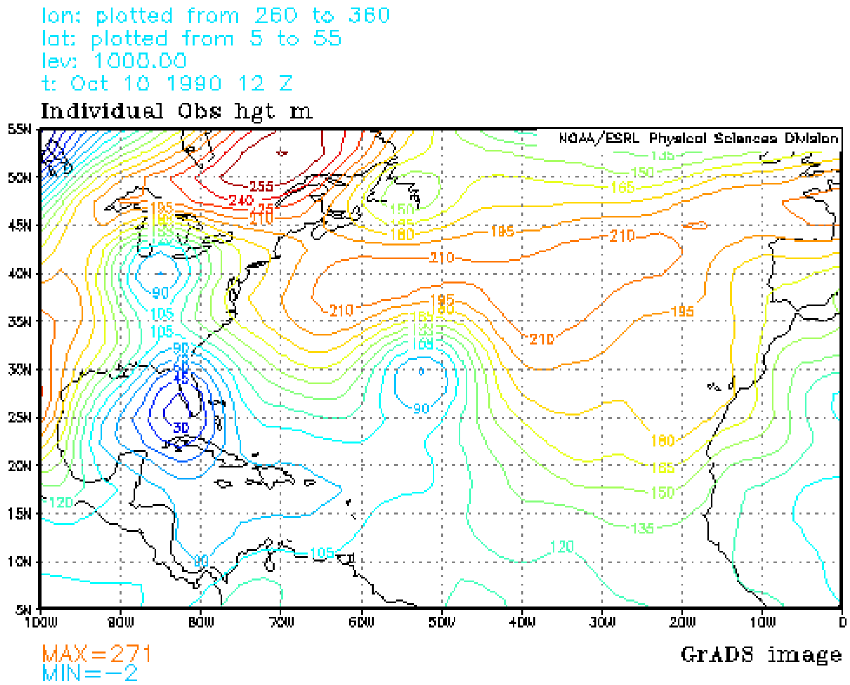


Figure 14. Plots of geopotential height for Type I Lili (1990) at 12 hours prior to genesis for (upper) 200 hPa and (lower) 1000 hPa levels.

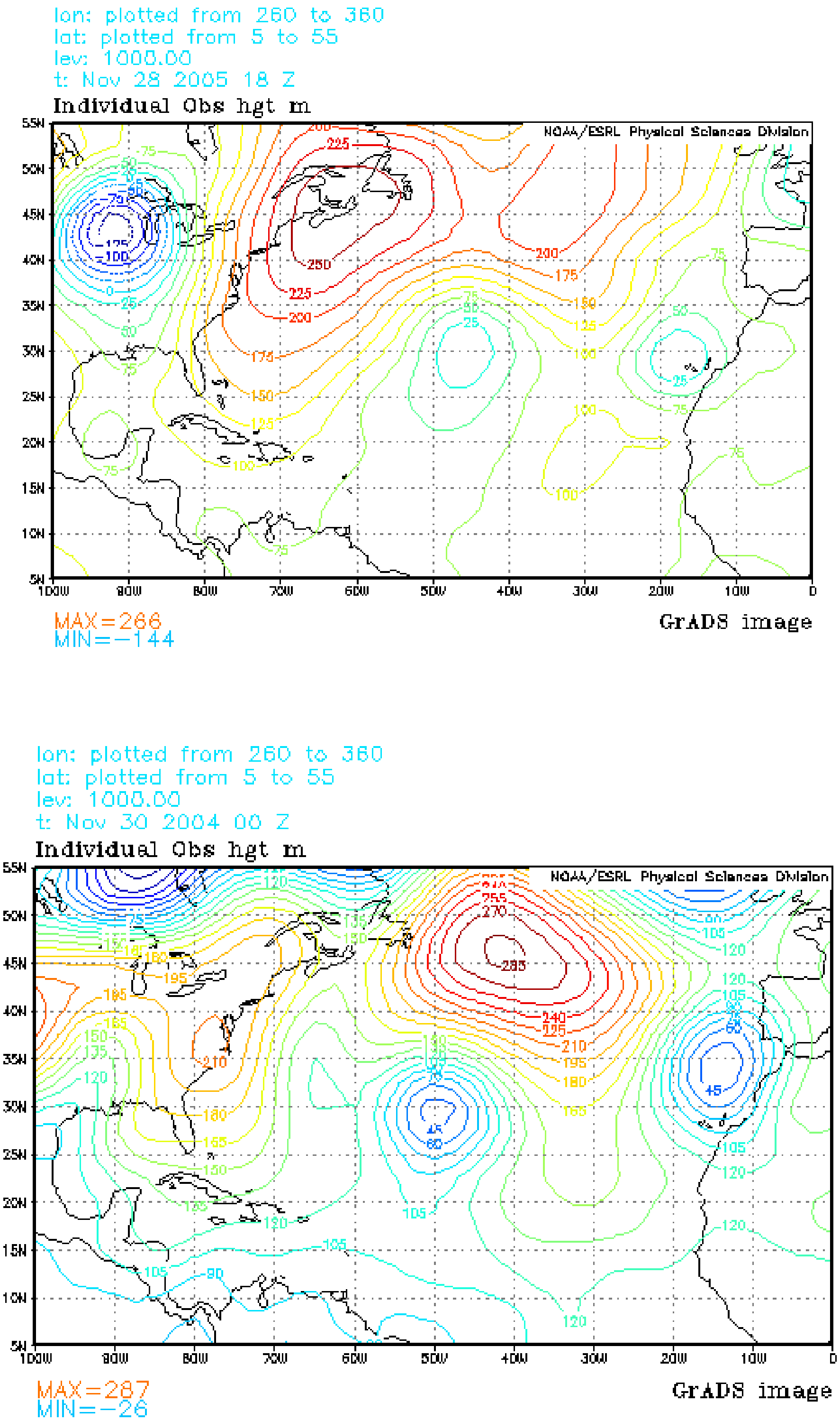


Figure 15. Plots of geopotential height for Type IIs (upper) Epsilon (2005) and (lower) Otto (2004) 12 hours prior to genesis at 1000 hPa level.

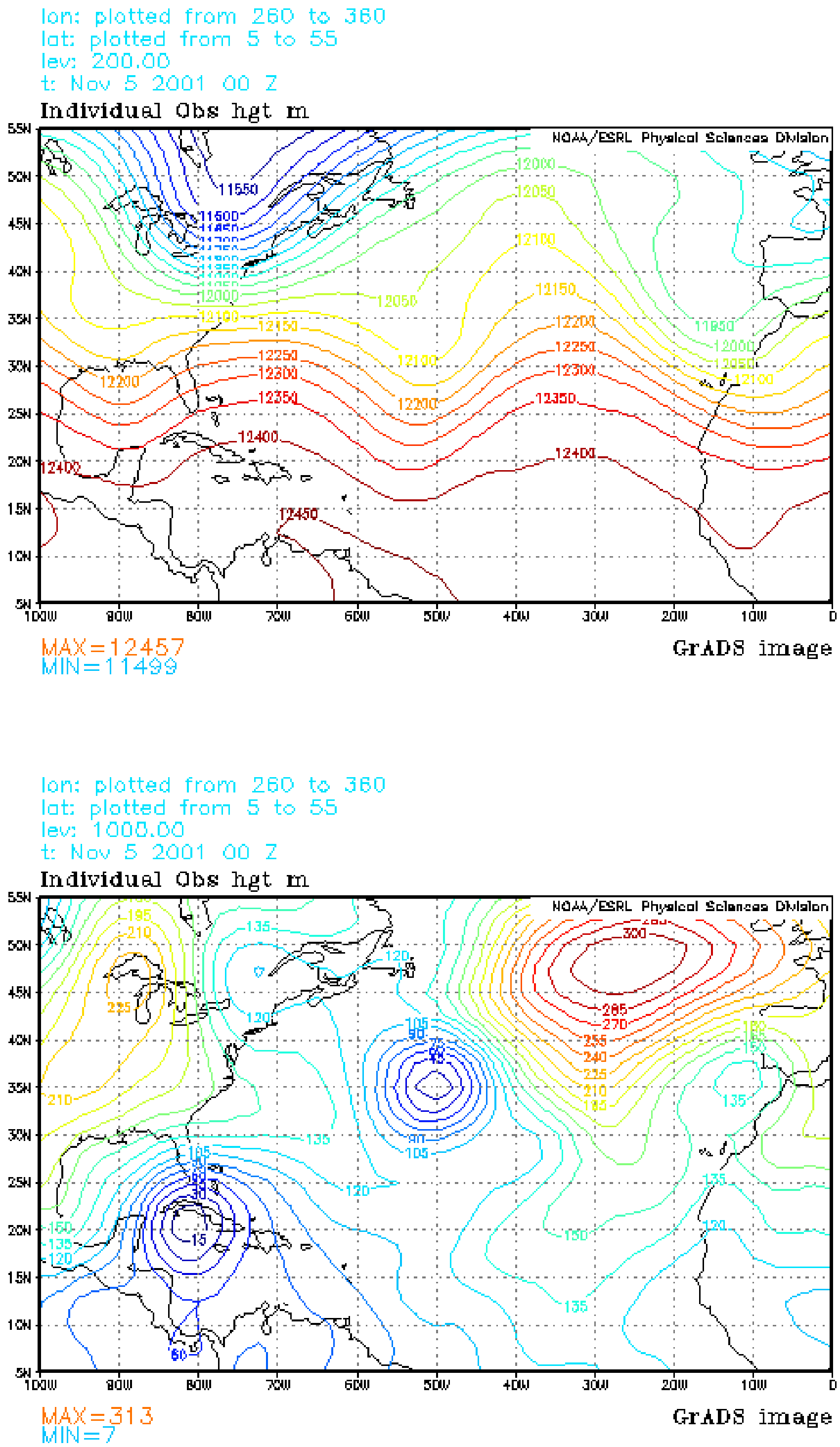
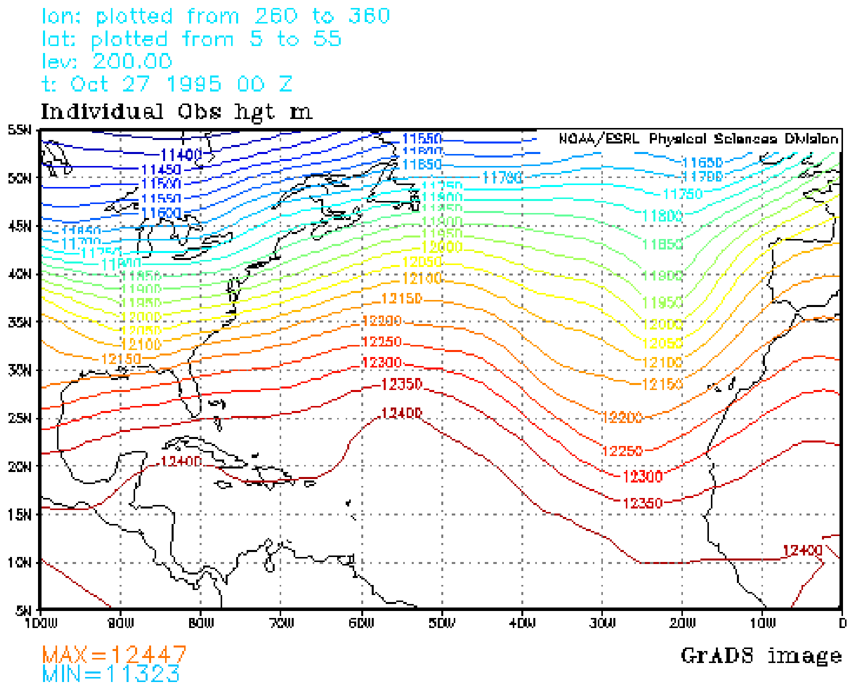


Figure 16. Plots of geopotential height for Type III Noel (2001) at 12 hours prior to genesis for (upper) 200 hPa and (lower) 1000 hPa levels.



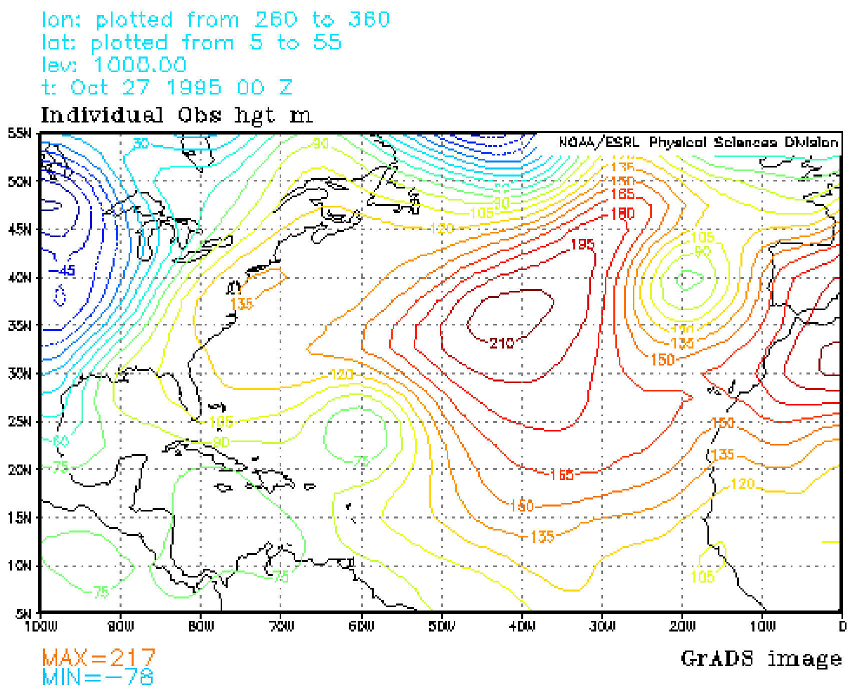


Figure 17. Plots of geopotential height for Type IV Tanya (1995) at 12 hours prior to genesis for (upper) 200 hPa and (lower) 1000 hPa levels.